Fifth Quantum Thermodynamics Conference (QTD5)

Oxford, 13-17 March 2017

Booklet of Abstracts

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Sunday 12th March	
17:00-	Registration
Monday 13th March	
08:00-08:50	Registration
08:50-09:00	Opening Remarks
09:00-09:30	**Roberta Zambrini** Entropy production and thermodynamic power of the squeezed thermal reservoir
09:30-09:55	**Marti Perarnau-Llobet** Work, entropy production, and heat engines beyond the weak coupling regime
09:55-10:20	**Ahsan Nazir** Performance of a quantum heat engine at strong reservoir coupling
10:20-10:45	**Eric Brown** The dynamics of a harmonic Otto engine
10:45-11:15	Coffee break
11:15-11:40	**Géraldine Haack** The energetic cost of entanglement genesis based on a quantum trajectory approach
11:40-12:05	**Philippe Faist** Fundamental work cost in implementations of quantum processes
12:05-12:30	**Lucas Céleri** Measurement of work distribution in structured light
12:30-12:55	**Irene d'Amico** Theoretical and experimental DFT-inspired method for the work distribution of a quantum many-body system
12:55-14:30	LUNCH
14:30-15:30	**Bar-Gill** NV centers in diamond - a potential platform for quantum thermodynamics
15:30-17:00	Breakout discussion — Working group meeting
17:00-17:30	**Shuoming An** Quantum thermodynamics with the trapped ion system
17:30-17:45	**Senaida Hernandez** Decay of correlations in long-range interacting systems at non-zero temperature
17:45-18:00	**Nicolai Friis** Passivity and practical work extraction using Gaussian operations
18:00-18:25	**Samu Suomela** Quantum thermodynamics in the presence of a finite-size environment

Tuesday 14th March	
09:00-09:30	**Renato Renner** Thermodynamics as a multi-agent theory
09:30-09:55	**Jose Alonso-Castaneda** Thermodynamics of weakly measured quantum systems
09:55-10:20	**Michele Campisi** Two-point measurement of quantum information scrambling
10:20-10:45	**Alexia Auffeves** The role of quantum measurement in quantum thermodynamics
10:45-11:10	Coffee break
11:10-11:40	**Mihai Vidrighin** Realisation of a Photonic Maxwell's Demon
11:40-12:05	**Katarzyna Macieszczak** Metastability in open quantum dynamics
12:05-12:30	**Juan Pablo Paz** Fundamental limit for cooling in driven quantum systems
12:30-12:55	**Wolfgang Niedenzu** On the operation of machines powered by quantum non-thermal baths
12:55-14:30	LUNCH
14:30-15:30	**Johan Aberg** Fully quantum fluctuation theorems
15:30-17:00	Breakout discussion — Working group meeting
17:00-17:30	**Kavan Modi** Enhancing the charging power of quantum batteries
17:30-17:55	**Elisa Bäumer** Work Extraction in Ion Traps
17:55-18:20	**Inanc Adagideli** Work Extraction and All Electrical Detection of the Landauer Principle in a Quantum Spin Hall Device
18:30	**Poster Session**

Wednesday 15th March	
09:00-09:30	**Anna Sanpera** Generalized fluctuation-dissipation relation for quantum Markovian systems
09:30-09:55	**Jordi Mur Petit** Quantum fluctuation relations for generalized Gibbs ensembles
09:55-10:20	**Giacomo De Palma** Universal locality of quantum thermal susceptibility
10:20-10:45	**Gabriele de Chiara** Out-of-equilibrium thermodynamics in ultracold atoms
10:45-11:15	Coffee break
11:15-11:40	**Robert Whitney** Non-Markovian quantum thermodynamics: second law and fluctuation theorems
11:40-12:05	**Marco Pezzutto** Implications of non-Markovian quantum dynamics for the Landauer
12:05-12:30	**Hiroyasu Tajima** Large Deviation implies First and Second Laws of Thermodynamics
12:30-12:45	**Philipp Kammerlander** An operational formulation of thermodynamics makes the zeroth law obsolete
12:45-13:00	**Henrik Wilming** The third law for finite non-equilibrium resources
13:00-14:30	LUNCH
14:30	MC meeting / Oxford city tour

Thursday 16th March	
09:00-09:30	**Nicole Yunger Halpern** Quantum chaos: A Jarzynski-like equality
09:30-09:55	**Mischa Woods** Autonomous quantum machines and finite sized clocks
09:55-10:20	**Andrea Mari** Finite-time dynamics and thermodynamics of open quantum systems
10:20-10:45	**Hugo Terças** Quantum thermal machines driven by vacuum force
10:45-11:10	Coffee break
11:10-11:40	**Bernhard Rauer** Recurrence of an isolated quantum many-body system
11:40-12:10	**Takahiro Sagawa** Fluctuation theorem for pure quantum states
12:10-12:35	**Adolfo del Campo** Quantum supremacy of many-particle thermal machines
12:35-13:00	**Kosuke Ito** Optimal performance of generalized heat engines with finite-size baths of arbitrary multiple conserved quantities based on non-i.i.d. scaling
13:00-14:30	LUNCH
14:30-15:30	**Christian Gogolin** Pure state quantum statistical mechanics
15:30-17:00	Breakout discussion — Working group meeting
Industry session	17:00 **Bruno Leone** *(ESA)*
	17:25 **Denise Powell** *(IQE)*
	17:45 **Mark Farries** *(Gooch & Housego)*
	18:05 **Ulrik Imberg** *(Huawei)*
	18:25 *Discussion & Questions*
19:00	Conference dinner

Friday 17th March	
09:00-09:30	**Joan Vaccaro** Sharing quantum coherence (and other asymmetries)
09:30-09:55	**Nayeli A. Rodríguez-Briones** Heat bath algorithmic cooling with correlated qubit-environment interactions
09:55-10:20	**Alexandre Roulet** Quantum Absorption Refrigerator in the Single-Shot Regime
10:20-10:45	**Patrick P. Hofer** Quantum thermal machines based on microwave resonators coupled to a Josephson junction
10:45-11:10	Coffee break
11:10-11:40	**Fred Jendrzejewski** Observation of the phononic Lamb shift with a synthetic vacuum
11:40-12:05	**Alhun Aydin** A torque induced by matter waves as a new macroscopic quantum phenomenon
12:05-12:30	**Roberto Serra** Experimental rectification of entropy production by a Maxwell's Demon in a quantum system
12:30-13:00	**Poster prize winners presentations**
13:00:13:10	Closing remarks
13:10	LUNCH

Talks

Monday 13^{th} March

Entropy production and thermodynamic power of the squeezed thermal reservoir

Roberta Zambrini

Instituto de Física Interdisciplinar y sistemas Complejos, Palma de Mallorca - Spain

Abstract: We analyze the entropy production and the maximal extractable work from a squeezed thermal reservoir. The nonequilibrium quantum nature of the reservoir induces an entropy transfer with a coherent contribution while modifying its thermal part, allowing work extraction from a single reservoir, as well as great improvements in power and efficiency for quantum heat engines. Introducing a modified quantum Otto cycle, our approach fully characterizes operational regimes forbidden in the standard case, such as refrigeration and work extraction at the same time, accompanied by efficiencies equal to unity.

Work, entropy production, and heat engines beyond the weak coupling regime

Marti Perarnau-Llobet[1,2], Arnau Riera[1], Rodrigo Gallego[3], Henrik Wilming[3], Jens Eisert[3]

[1]ICFO - Spain
[2]Max Planck Institute of Quantum Optics, Garching - Germany
[3]FU Berlin - Germany

Abstract: Recent years have seen an enormously revived interest in the study of thermodynamic notions in the quantum regime. This applies both to the study of thermal machines in the quantum regime, as well as to questions of equilibration and thermalisation of interacting quantum many-body systems as such. In this work we bring together these two lines of research by studying thermodynamic protocols for systems that interact strongly with thermal baths. In this case, the system does not equilibrate to a thermal state of its internal Hamiltonian, although equilibration is still guaranteed. The equilibration of the system can be broadly described within these two models: (i) equilibration to the reduced of a global thermal state contain-

ing system and bath, i.e., thermalisation of the whole interacting ensemble, and (ii) equilibration to a Generalized Gibbs Ensemble, where more quantities than energy are conserved due to, e.g., symmetries in exactly solvable many-body systems. In our work we study work extraction, entropy production, and heat engines within these two models of equilibration. For the model (i), we derive exact corrections to the second law of thermodynamics (in its different formulations) in the weak coupling regime which can be applied for arbitrary interacting systems. In particular, we show that a finite coupling strength necessarily leads to irreversibility due to built-up of correlations. We then discuss the power of such strongly coupled thermal machines, showing that optimal power is reached for intermediate coupling strengths where the work per cycle is not optimal. Finally we exemplify all our results in the widely used Caldeira-Leggett model describing an harmonic oscillator within a thermal bosonic bath. To analyze power in this model we also present new results regarding equilibration times in the Caldeira-Leggett model which might be of independent interest. For the model of equilibration (ii), we construct effective descriptions for thermodynamic protocols in terms of Generalized Gibbs states (GGE). For such effective descriptions we study notions of entropy production and reversibility. In particular, we show that, although entropy production is guaranteed for the GGE states, in the limit of infinitesimally small transformations the entropy remains constant. We then connect these considerations to the minimal work principle. Finally, we compare the effective description in terms of GGE states with the real unitary dynamics, obtaining excellent agreement for fermionic system.

Work Extraction in Ion Traps

Elisa Bäumer[1], Philipp Kammerlander[1], Marti Perarnau-Llobet[2,3], Lídia Del Rio[1], Matteo Marinelli[1], Jonathan Home[1], Renato Renner[1]
[1]ETH Zurich - Switzerland
[2]ICFO - Spain
[3]Max Planck Institute for Quantum Optics - Germany

Abstract:
Motivation — According to Landauer's Principle the erasure of one bit, i.e. resetting a bit in an unknown state to a well-known reference state, costs at least $W = k_B T \ln 2$ work which is dissipated as heat into the environment at temperature T. In the opposite direction, using heat of a thermal bath at temperature T and the information of one initially pure qubit, one can extract at most $W = k_B T \ln 2$ work while the qubit turns into a fully mixed state. Since the formulation of Landauer's principle there have been experimental verifications in several set-ups, also in the quantum regime. However, only a few managed to explicitly store the extracted work and none were state-independent at the same time, that is, they all required to continuously track

the state of the system. Our goal was to implement a state-independent protocol in trapped ions that explicitly stores the extracted work in a microscopic degree of freedom.

Theoretical Model and Experimental Realization — We formulate a protocol in the spirit of the thermal operations framework. In order to realize a work extraction protocol, we need three systems: a battery S of information qubits, a thermal bath B at fixed temperature T, modelled as a set of qubits in the Gibbs state, and a work storage system W. While the total system is subject to an energy-conserving unitary, we can use the information of one initially pure battery qubit S to convert heat from the coupled thermal bath B into work stored in system W. In the experiment, the battery qubit S and thermal qubit B are represented by the internal states of two ions, while the work storage system W is represented by a common motional mode of these two ions. The unitary is achieved by a composition of π-pulses, Molmer-Sorensen gates and Red Sideband Transformations.

Contribution and Outlook — In collaboration with J. Home's Trapped Ion group (ETH Zurich) we developed a protocol for trapped ions that explicitly stores the extracted work in the motional mode of two trapped ions and that runs state-independently. We analysed the energy fluctuations during the evolution and used simulations to estimate the errors. The protocol is experimentally feasible and its implementation in the Trapped Ion group will be carried out in the beginning of next year.

The dynamics of a harmonic Otto engine

Eric Brown, Alejandro Pozas Kerstjens, and Karen Hovhannisyan

ICFO - Spain

Abstract: In this talk I will present results characterizing the full dynamics of a quantum harmonic Otto engine, in which the working body is a harmonic oscillator and the heat baths are collections of oscillators. By harmonically interacting the working body with the baths we are able to exactly solve the system dynamics during an engine stroke, and thus the dynamics of the cycle as a whole. With this approach we are able to study the efficiency and total work output of the engine, and how these are impacted by finite bath sizes, bath structures, and particle-creation due to the interaction quenches and the quench timescale (i.e. switching on and off the interaction between the working oscillator and the baths). We also analyse the correlations that build up between the working oscillator and the baths, and correlations that build between the baths themselves, and how these impact the workings of the engine. In this way we are starting to get a grasp on many of the destabilizing effects that are to be expected in any real laboratory implementation of a quantum Otto engine, and the avenues available for their minimization.

The energetic cost of entanglement genesis based on a quantum trajectory approach

Géraldine Haack[1], Cyril Elouard[2], Alexia Auffeves[2]

[1]University of Geneva - Switzerland

[2]University of Grenoble Alpes (Institut NEEL) - France

Abstract: We confront a thermodynamical approach with a quantum information approach to characterize the energetic counterpart of entanglement genesis. More precisely, motivated by recent experiments that have demonstrated the generation of entanglement between two distant superconducting qubits by measuring their parity, we focus in this work on the energetic cost of parity measurement-induced entanglement. Based on a quantum trajectory approach, our main result states that entanglement genesis between two qubits, intimately related to the loss of coherence between the two parity subspaces, is associated with a dissipation process of quantum heat only, i.e. a heat that has no classical counterpart. We complete this study by expressing the concurrence in terms of this quantum heat and we show that generating entanglement via a QND-parity measurement is associated with a smaller internal energy variation than entanglement genesis through the implementation of a set of universal logical gates. These results lead us to explicit the fundamental relation that exists between quantum information and thermodynamics for one of the most important quantum features, entanglement.

Fundamental work cost in implementations of quantum processes*

Philippe Faist[1], Renato Renner[2]

[1]Caltech - United States

[2]ETH Zurich - Switzerland

Abstract: The search for the ultimate laws of thermodynamics at the nano scale is providing ever deeper insights on the constraints on implementations of information processing. The work requirement for erasure and work yield of formation of a quantum state, the conversion rates of one state into another as well as the work cost of logical processes on systems with a trivial Hamiltonian have been successfully characterized. Here, we provide a general fundamental lower limit, valid for systems with an arbitrary Hamiltonian and in contact with a heat bath, on the work cost for the implementation of any logical process. This limit is given by a new information measure —the coherent relative entropy— which measures information relative to the Gibbs weight of each microstate. Our limit is derived using Gibbs-preserving maps, which are the most tolerant operations one can allow for free without render-

*The details are provided in [Ph. Faist, Ph.D. thesis (2016) arXiv:1607.03104], and are the subject of a manuscript in preparation.

ing the theory trivial, and hence ensuring our bound also holds in the context of other frameworks such as thermal operations. The coherent relative entropy enjoys properties such as a data processing inequality and a chain rule, which justifies its interpretation as an information measure. In the limit of many independent repetitions of the process, or alternatively if the input and output states happen to be Gibbs states, then the coherent relative entropy coincides with the difference of the relative entropies of the input and the output state to the Gibbs state. This latter property allows us to recover macroscopic thermodynamics as emergent from our microscopic model.

Our framework is furthermore well suited for relating different observers which may have different levels of knowledge about the system. If an observer Bob describes a situation in which Gibbs-preserving maps may be applied to two systems SM, but Alice is only able to observe S, she may describe the same situation as Gibbs-preserving maps being applied on S, where the Gibbs state on S is obtained by tracing out the joint Gibbs state on SM. Hence we may interpret our framework as an observer-dependent generalization of thermodynamics, which may be used to describe systems by observers possessing different levels of knowledge about a system.

Measurement of work distribution in structured light

Renné De Araújo , Paulo Souto Ribeiro, Lucas Céleri

Universidade Federal de Goiás - Brazil

Abstract: Optical systems are a useful tool to study the evolution of quantum systems. This is possible since the paraxial equation, describing the propagation of beams of light, is formally identical to the Schrodingers equation. In this analogy, the transverse spatial profile of light plays the role of a two-dimensional quantum wave function, whereas the propagation distance plays the role of the time of evolution. In this work, we use a Spatial Light Modulator to implement a process on the spatial profile of a Laguerre-Gaussian (LG) beam. The optical-quantum analogy allows us to interpret this process as a quantum evolution doing work on a system initially at an eigenstate of the orbital angular momentum of light. A series of projective measurements with different LG modes in the input provides information on the quantum work distribution (and entropy production) of the process, an experimental result that provides a new platform to the yet poorly explored field of quantum thermodynamics. Due to the infinite dimensional character of the angular momentum space, this platform provides a very powerful tool in the study of thermodynamic properties of information processing.

Theoretical and experimental DFT-inspired method for the work

distribution of a quantum many-body system †

Irene D'Amico[1], Marcela Herrera[2], Roberto Serra[1,2]

[1]University of York - UK

[2]Universidade Federal Do ABC - Brazil

Abstract: To understand how the increase of disorder in the macroscopic world follows from microscopic order we need to determine the so-called work distribution (which is related to the entropy production) for quantum systems performing suitable cyclic dynamics. This is a crucially difficult task, particularly so when interacting many-particle (or many-spin) systems are considered. Here we study the quantum fluctuations of a many-body system by proposing a new method inspired by density functional theory (DFT). DFT is one of the most powerful methods to calculate realistic estimates for the properties of many-body systems. However so far it has not been applied to the study of quantum work. Through the method we propose, we can estimate the transition matrix elements due to the system time-dependent dynamics and obtain an approximation to the work distribution and average work of a driven quantum many-body system. The method is general and could be in principle be applied to any many-body system. Our method allows to 'map' the interacting system into a special non-interacting system (Kohn-Sham system), still yielding very accurate results. We apply this DFT-inspired approach to obtain the work distribution function of a driven Hubbard dimer. This model can represent different quantum system, as for example electron dynamics in coupled quantum dots driven by applied fields. We compare results from the new method with the exact results and show that this approximation is very effective under a very wide range of parameters, including sudden quench, non-adiabatic dynamics, and adiabatic dynamics. Within this wide range of parameters, we in fact obtain results for the average work that are within 10% of the exact results. We also show how the method can be used to design a new experimental protocol for the measure of the work distribution of many-body systems.

NV centers in diamond - a potential platform for quantum thermodynamics

Nir Bar-Gill

The Hebrew University of Jerusalem - Israel

Abstract: Nitrogen Vacancy (NV) centers in diamond have emerged over the past few years as well-controlled quantum systems, with promising applications ranging from quantum information science to sensing. In addition, the fact that NVs are coupled to baths of other spin defects present in the lattice,

†The authors acknowledge support from Royal Society Grant NA140436.

make them uniquely suitable for studies of quantum thermodynamics of spin baths. In this tutorial, I will first introduce the NV center system and the experimental methods used for measuring them and controlling their quantum spin dynamics. I will then describe the system as a platform for quantum thermodynamic experiments, presenting recent experiments on cooling of an electronic spin bath through polarization transfer from the NVs to the bath, based on an analog of the Hartmann-Hahn double-resonance scheme [1,2]. In these experiments, we demonstrate enhanced polarization transfer from the NV to the bath, manifest as a two-order of magnitude reduction of the NV lifetime. Finally, I will mention current and future efforts in studying thermalization control in driven systems [3] and dissipative dynamics in driven open quantum systems, based on the NV platform [4].

[1] C. Belthangady, N. Bar-Gill, L. M. Pham, K. Arai, D. Le Ssage, P. Cappellaro, R. L. Walsworth, Phys. Rev. Lett. 110, 157601 (2013).

[2] S. R. Hartmann, E. L. Hahn, Phys. Rev. 128, 2042 (1962).

[3] D. D. Bhaktavatsala Rao, D. Gelbwaser-Klimovsky, N. Bar-Gill, G. Kurizki, (submitted).

[4] Y. Hovav, H. Inbar, H. Weimer, N. Bar-Gill, (in preparation).

Quantum thermodynamics with the trapped ion system

Shuoming An

Tsinghua University, Beijing - China

Abstract: The experimental study of the quantum thermodynamics is an attractive topic. The trapped ion system is extremely suitable for this task for its clean single particle nature and the efficient quantum control. Here we will report the first experimental demonstration of the quantum Jarzynski equality with a single trapped ion, along which we utilize the adiabatic shortcut. For the wide application of the adiabatic process in the quantum thermodynamics study, we will also report the first demonstration of the adiabatic shortcut in the transitionless way. Later we extend the quantum Jarzynski equality in the closed system to a quasi-open system. Finally we will introduce our future plan for the application of quantum reservoir engineering, which will be essential for the quantum heat engine and the quantum thermodynamics in the open system.

Decay of correlations in long-range interacting systems at non-zero temperature

Senaida Hernández-Santana[1], Christian Gogolin[1,2], Ignacio Cirac[2], Antonio Acín[1,3]

[1]ICFO - Spain, [2]Max Planck Institute of Quantum Optics, Garching - Germany,

[3]Institució Catalana de Recerca i Estudis Avançats, Barcelona - Spain

Abstract: While the locality of correlation functions has been widely studied for 1D systems with short-range interactions, little is known about long-range interacting systems at non-zero temperature. In this work, we study how correlations behave in a system with long-range interactions in thermal equilibrium. In particular, we consider density density correlations in a generalization of the Kitaev chain for fermions with long-range p-wave pairing, decaying with distance as a power-law with exponent α. We demonstrate that correlations asymptotically follow a power-law with exponent ν. In general, the exponent ν does not depend on the temperature away from criticality and two behaviours are observed: either the interactions are characterized by $\alpha < 1$ and the exponent $\nu \sim 2$, or $\alpha \geq 1$ and the exponent $\nu = 2\alpha$. In addition, we prove that correlation functions of anticommutative observables decay at least as a power law at non-zero temperature for fermionic and two-site long-range interacting Hamiltonians.

Passivity and practical work extraction using Gaussian operations

Eric Brown[1], Nicolai Friis[2], Marcus Huber[3]

[1]ICFO - Spain
[2]University of Innsbruck - Austria
[3]Institute for Quantum Optics and Quantum Information, Vienna - Austria

Abstract: Quantum states that can yield work in a cyclical Hamiltonian process form one of the primary resources in the context of quantum thermodynamics. Conversely, states whose average energy cannot be lowered by unitary transformations are called passive. However, while work may be extracted from non-passive states using arbitrary unitaries, the latter may be hard to realize in practice. It is therefore pertinent to consider the passivity of states under restricted classes of operations that can be feasibly implemented. Here, we ask how restrictive the class of Gaussian unitaries is for the task of work extraction. We investigate the notion of Gaussian passivity, that is, we present necessary and sufficient criteria identifying all states whose energy cannot be lowered by Gaussian unitaries. For all other states we give a prescription for the Gaussian operations that extract the maximal amount of energy. Finally, we show that the gap between passivity and Gaussian passivity is maximal, i.e., Gaussian-passive states may still have a maximal amount of energy that is extractable by arbitrary unitaries, even under entropy constraints.

Quantum thermodynamics in the presence of a finite-size environment

Samu Suomela[1], Aki Kutvonen[1,2], Rui Sampaio[1], Tapio Ala-Nissila[1,3]

[1]Aalto University - Finland
[2]University of Tokyo - Japan

[3]Brown University - United States

Abstract: Measuring the thermodynamic properties of open quantum systems poses a major challenge. A calorimetric detection [1] has been proposed as a feasible experimental scheme to measure work and fluctuation relations in open quantum systems. However, the detection requires a finite size for the environment, which in uences the system dynamics. This process cannot be modeled with the Lindblad equation and it's stochastic unravelings. In this talk, we present a recently developed model [2-4] that takes into account the finite-size of the environment. In the model, the environment is assumed to decohere faster than the other time scales. For the model, we microscopically derive a Lindblad-like master equation [3]. We also show that the master equation can be unravelled into stochastic trajectories [2] of the system that depend on the own history through the state of the environment. Thus, from the point of view of the system's degrees of freedom, the trajectories are non-Markovian. With the method we study the common uctuation relations and prove that they are satisfied [2].

[1] J. P. Pekola, P. Solinas, A. Shnirman, and D. V. Averin, New J. Phys., 15(11):115006 (2013).

[2] S. Suomela, A. Kutvonen, and T. Ala-Nissila, Phys. Rev. E 93, 062106 (2016).

[3] S. Suomela, R. Sampaio, and T. Ala-Nissila, Phys. Rev. E 94, 032138 (2016).

[4] J. P. Pekola, S. Suomela, and Y. Galperin, J. Low Temp. Phys. 184, 1015 (2016).

Tuesday 14^{th} March

Thermodynamics as a multi-agent theory

Renato Renner

ETH Zurich - Switzerland

Abstract: In modern approaches to thermodynamics, entropy is not regarded as an (objective) property of a system, but rather reflects the (subjective) knowledge that an agent has about it. In other words, different agents would generally assign different entropies to the same system. In this talk, I will take this subjective approach one step further and describe thermodynamics as a multi-agent theory. This raises novel questions, e.g., under which conditions two different agents thermodynamic descriptions of a system can be considered consistent?

Thermodynamics of weakly measured quantum systems

Jose Alonso Castaneda

Friedrich Alexander University of Erlangen-Nürnberg - Germany

Abstract: We consider continuously monitored quantum systems and introduce definitions of work and heat along individual quantum trajectories that are valid for coherent superposition of energy eigenstates. We use these quantities to extend the first and second laws of stochastic thermodynamics to the quantum domain. We illustrate our results with the case of a weakly measured driven two-level system and show how to distinguish between quantum work and heat contributions. We finally employ quantum feedback control to suppress detector backaction and determine the work statistics.

Two-point measurement of quantum information scrambling[‡]

Michele Campisi[1], John Goold[2]

[1]Scuola Normale Superiore di Pisa - Italy

[2]The Abdus Salam International Centre for Theoretical Physics, Trieste - Italy

Abstract: Scrambling of quantum information can be conveniently quantified by so called out-of-time-order-correlators (OTOC's), i.e. correlators

[‡]Michele Campisi and John Gold, arXiv:1609.05848

of the type $(W_\tau^\dagger V^\dagger W_\tau V)$, whose measurements presents a formidable experimental challenge. Here we report on a method for the measurement of OTOC's based on the so-called two-point measurements scheme developed in the field of non-equilibrium quantum thermodynamics. The scheme is of broader applicability than methods employed in current experiments and also provides a clear-cut interpretation of quantum information scrambling in terms of non-equilibrium fluctuations of thermodynamic quantities such as work.

The role of quantum measurement in quantum thermodynamics[§]

Alexia Auffeves[1], Cyril Elouard[1], Maxime Clusel[2], David Herrera Marti[1]

[1]University of Grenoble Alpes (Institut NEEL) - France

[2]Université Montpellier II - France

Abstract: In this talk I propose a new formalism for stochastic thermodynamics in the quantum regime, where stochasticity and irreversibility primarily come from quantum measurement. In the absence of any bath, a purely quantum component to heat exchange is defined, that corresponds to energy uctuations caused by measurement back-action. Energetic and en tropic signatures of measurement induced irreversibility are investigated for canonical experiments of quantum optics, and the energetic cost of counter-acting decoherence is characterized on a simple state-stabilizing protocol. By placing quantum measurement in a central position, this formalism contributes to bridge a gap between experimental quantum optics and quantum thermodynamics.

Realisation of a Photonic Maxwell's Demon

Mihai Vidrighin

Imperial College London - UK, University of Oxford - UK

Abstract: We present an experimental implementation of Maxwells demon in a photonic setup. We show that a measurement at the few-photons-level- applied to intense thermal light and accompanied by feedback- can allow extraction of work into an electric circuit. This implementation pinpoints some challenges that arise when putting the thought experiment into practice and leads us to derive an equality relating work extraction to information acquired by measurement. Using this- we derive a bound on the extracted work distribution- which we show to be in agreement with the experimental results. Our work puts forward photonic systems as an experimental platform

[§]Elouard, Herrera-Marti, Clusel, Auffeves, *The role of quantum measurement in stochastic thermodynamics*, arXiv: 1607.02404, under review at Nature Quantum Information (2016) for information thermodynamics.

Metastability in open quantum dynamics

Katarzyna Macieszczak

University of Nottingham - UK

Abstract: We discuss metastability for open quantum systems with Markovian dynamics. Metastability is a common phenomenon in which the system's initial relaxation into long-lived metastable states is followed by the decay to a true stationary state at much longer times. This separation of timescales necessarily requires a splitting in the spectrum of the dynamics generator. We show how to exploit this spectral structure in order to obtain a low dimensional mapping of both the metastable manifold and the effective dynamics within [1]. We illustrate the usefulness and simplicity of this method by unravelling long-lived features in a quantum Ising chain with dissipation [2] and in a quantum glass model [3].

[1] K. Macieszczak, M. Guta, I. Lesanovsky, J. P. Garrahan, Phys. Rev. Lett. 116, 240404 (2016).

[2] D. C. Rose, K. Macieszczak, I. Lesanovsky, and J. P. Garrahan, Phys. Rev. E 94, 052132 (2016).

[3] K. Macieszczak, D. C. Rose, I. Lesanovsky, J. P. Garrahan, (in preparation).

Fundamental limit for cooling in driven quantum systems

Juan Pablo Paz

Universidad de Buenos Aires - Argentina

Abstract: will study the asymptotic behavior of quantum refrigerators consisting of a parametrically driven quantum network which is coupled with an arbitrary number of thermal reservoirs. I will show that this type of refrigerator can never cool a cold reservoir beyond certain minimal (non universal) temperature. The process that enforces this fundamental limit for cooling is very general: the non resonant creation of excitations pairs in the reservoirs. This process is closely related with the dynamical Casimir effect and seems to be the one responsible for the validity of the dynamical version of the third law of thermodynamics (Nernst unattainability principle). We apply the result to find, for example, the lowest attainable temperature for sideband laser cooling.

Universal thermodynamic limit of quantum engine efficiency

Wolfgang Niedenzu, Victor Mukherjee[1], Arnab Ghosh[1],
Abraham G. Kofman[1,2], Gershon Kurizki[1]

[1]Weizmann Institute of Science - Israel

[2]CEMS, RIKEN, Saitama - Japan

Abstract: The efficiency of heat engines is limited by the Carnot bound, attained when the engine cycle is reversible. Quantum engines fuelled by non-thermal (e.g., squeezed-thermal) baths have been shown to surpass this bound. Yet, their maximum efficiency cannot be determined by the reversibility condition, which may yield an unachievable efficiency bound above 1. This prompts the question: What does really limit the efficiency? We identify the fraction of the exchanged energy between a quantum system and a bath that necessarily causes an entropy change and derive a new inequality for the latter. This formulation reveals a universal efficiency bound for quantum engines which is invariably attained for the least dissipation over the engine cycle but does not imply reversibility, unless the baths are thermal. This bound thus cannot be solely deduced from the laws of thermodynamics. We illustrate these results for the practically-relevant Carnot- and Otto cycles energised by non-thermal baths, which are both shown to be restricted by our new efficiency bound.

Fully quantum fluctuation theorems

Johan Åberg

University of Cologne - Germany

Abstract: The work required to drive systems out of thermal equilibrium is typically random on microscopic scales. Crooks fluctuation theorem relates the distribution of these random work costs with the corresponding distribution for the reverse process. We discuss a quantum generalisation that not only describes the energy costs- but also includes coherences. This approach moreover opens up for further generalisations- such as ‘conditional’ fluctuation relations that are applicable to non-equilibrium initial states- as well as approximate fluctuation relations that allow for models where the evolution is generated by a global time-independent Hamiltonian.

Enhancing the charging power of quantum batteries

Kavan Modi

Monash University, Victoria - Australia

Abstract: Can collective quantum effects make a difference in a meaningful thermodynamic operation? Focusing on energy storage and batteries-

we demonstrate that quantum mechanics can lead to an enhancement in the amount of work deposited per unit time- i.e.- the charging power- when N batteries are charged collectively. We first derive analytic upper bounds for the collective quantum advantage in charging power for two choices of constraints on the charging Hamiltonian. We then highlight the importance of entanglement by proving that the quantum advantage vanishes when the collective state of the batteries is restricted to be in the separable ball. Finally- we provide an upper bound to the achievable quantum advantage when the interaction order is restricted- i.e.- at most k batteries are interacting. Our result is a fundamental limit on the advantage offered by quantum technologies over their classical counterparts as far as energy deposition is concerned.

Performance of a quantum heat engine at strong reservoir coupling

Dave Newman[1], Florian Mintert[1], Ahsan Nazir[2]

[1]Imperial College London - UK

[2]University of Manchester - UK

Abstract: We study a quantum heat engine at strong coupling between the system and the thermal reservoirs. Exploiting a collective coordinate mapping, we incorporate system-reservoir correlations into a consistent thermodynamic analysis, thus circumventing the usual restriction to weak coupling and vanishing correlations. We apply our formalism to the example of a quantum Otto cycle, demonstrating that the performance of the engine is diminished in the strong coupling regime with respect to its weakly coupled counterpart, producing a reduced net work output and operating at a lower energy conversion efficiency. We identify costs imposed by sudden decoupling of the system and reservoirs around the cycle as being primarily responsible for the diminished performance, and define an alternative operational procedure which can partially recover the work output and efficiency. More generally, the collective coordinate mapping holds considerable promise for wider studies of thermodynamic systems beyond weak reservoir coupling, and we shall also discuss the potential for strong reservoir coupling effects to enhance power output in finite time engines.

Experimental rectification of entropy production by a Maxwell's Demon in a quantum system

Roberto Serra

University of York - UK, Universidade Federal Do ABC - Brazil

Abstract: Maxwell's demon explores the role of information in physical processes. Employing information about microscopic degrees of freedom, this "intelligent observer" is capable of compensating entropy production (or

extracting work), apparently challenging the second law of thermodynamics. Theoretical endeavors to incorporate information into thermodynamics acquire a pragmatic applicability within the recent technological progress, where information just started to be manipulated at the micro and nanoscale. A modern framework for these endeavors has been provided by explicitly taking into account the change, introduced in the statistical description of the system, due to the assessment of its microscopic information. This outlines an illuminating paradigm for the Maxwell's demon, where the information-to-energy conversion is governed by fluctuation theorems, which hold for small systems arbitrarily far from equilibrium. Generalizations of the second law in the presence of feedback control can be obtained from this framework, establishing bounds for information-based work extraction. Notwithstanding its fundamental relevance, these relations do not provide a clear recipe for building a demon in a laboratory setting. We contribute to the aforementioned efforts deriving an equality concerning the information-to- energy conversion for a quantum non-unitary feedback process. Such relation involves a trade-off between information-theoretic quantities that provides a recipe to design and implement an effcient Maxwell's demon in a quantum system where coherence is present. Supported by this trade-off relation and employing Nuclear Magnetic Resonance (NMR) spectroscopy, we set up an experimental coherent implementation of a measurement-based feedback. Furthermore, we quantify experimentally the effectiveness of this Maxwell's demon to rectify entropy production, due to quantum uctuations, in a non-equilibrium dynamics. The demon is experimentally implemented as a spin-1/2 quantum memory that acquires information, and employs it to control the dynamics of another spin-1/2 system, through a natural interaction. This realization provides experimental evidence that the irreversibility in a non-equilibrium dynamics can be mitigated by assessing microscopic information and applying a feed-forward strategy at the quantum scale.

Wednesday 15^{th} March

Generalized fluctuation-dissipation relation for quantum Markovian systems

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Abstract: The fluctuation-dissipation theorem (FDT) is a central result in statistical physics, both for classical and quantum systems. It establishes a relationship between the linear response of a system under a time-dependent perturbation and time correlations of certain observables in equilibrium. Here we derive a generalization of the theorem which can be applied to any Markov quantum system and makes use of the symmetric logarithmic derivative (SLD). There are several important benefits when FDT's are formulated in terms of the SLD. First, such a formulation claries the relation between classical and quantum versions of the equilibrium FDT. Second, and more important, it facilitates the extension of the FDT to arbitrary quantum Markovian evolution, as given by quantum maps. Third, it brings out the connection between the FDT and Fisher information, which plays a crucial role in quantum metrology. In this Letter we prove a generalized FDT for generic quantum maps and illustrate these features in an example of two harmonic oscillators with a modulated interaction.

Quantum fluctuation relations for generalized Gibbs ensembles

Jordi Mur Petit[1], Armando Relaño[2], Rafael Molina[3], Dieter Jaksch[1,4]

[1]University of Oxford - UK

[2]Universidad Complutense de Madrid - Spain

[3]Instituto de Estructura de la Materia, Madrid - Spain

[4]National University of Singapore - Singapore

Abstract: The non-equilibrium dynamics of a strongly-correlated quantum system is one of the most fascinating problems in physics, with open questions such as whether and how the system will relax to an equilibrium state. Unusual phenomena are observed when the system exhibits conserved quantities that constrain its evolution in phase-space, invalidating the predictions of standard quantum thermodynamics. Here, we derive a set of exact results that relate out-of-equilibrium fluctuations in the energy and other observables with equilibrium properties in a system with conserved quantities,

and explore their implications on maximum work-extraction efficiency with quantum machines that rely on quantum and thermal fluctuations. We finally discuss potential tests of our findings with existing trapped-ion technology.

Out-of-equilibrium thermodynamics in ultracold atoms

Gabriele De Chiara

Queen's University Belfast - UK

Abstract: The study of out-of-equilibrium thermodynamics has received a significant thrust thanks to the experimental advances in the control and manipulation of microscopic systems. Work, an ubiquitous concept in traditional thermodynamics, assumes in this context the role of a stochastic variable whose uctuations can be ingeniously related to equilibrium properties, as is the case of the celebrated Jarzynski equality [1]. In this talk, I will revise these concepts and discuss feasible experimental schemes to directly measure work in cold atomic setups. I will show that the interaction between atoms and the light polarisation of a probe laser, as in atomic ensembles experiments, allows us to measure work uctuations through a homodyne measurement of the output light [2]. A second scheme allows one to measure the work done on an atomic BEC in a double well potential when the atomic self-interaction is varied. I will discuss strategies based on optimal control techniques to reduce the irreversible work production [3].

[1] C. Jarzynski, Phys. Rev. Lett. 78, 2690 (1997).

[2] G. De Chiara, A. J. Roncaglia, J. P. Paz, New J. Phys. 17, 035004 (2015).

[3] R. G. Lena, G. M. Palma, G. De Chiara, Phys. Rev. A 93, 053618 (2016)

Universal locality of quantum thermal susceptibility

Giacomo De Palma[1,2,3], Antonella De Pasquale[2,3], Vittorio Giovannetti[2,3]

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[2]Scuola Normale Superiore di Pisa - Italy

[3]NEST Istituto Nanoscienze-CNR, Pisa - Italy

Abstract: The ultimate precision of any measurement of the temperature of a quantum system is the inverse of the local quantum thermal susceptibility [1] of the subsystem with whom the thermometer interacts. If we have access to the global system, in a thermal (Gibbs) state, such quantity reduces to the variance of the system Hamiltonian, endowed with clear thermodynamical interpretation: it corresponds to the heat capacity of the system. In this work we explicitly extend such correspondence to a generic subpart of a locally interacting quantum system. We prove that the local quantum thermal susceptibility is close to the variance of its local Hamiltonian, provided the volume to surface ratio of the subsystem is much larger than the correlation

length. This result greatly simplifies the determination of the ultimate precision of any local estimate of the temperature, and rigorously determines the regime where interactions can affect this precision.

[1] De Pasquale et al., Nature Communications 7, 12782 (2016)

Non-Markovian quantum thermodynamics: second law and fluctuation theorems¶

Robert Whitney

Université Joseph Fourier and Université Grenoblé 1 - France

Abstract: We bring together Keldysh theory and quantum thermodynamics, by showing that a real-time diagramatic technique can provide a quantum equivalent of stochastic thermodynamics for non-Markovian quantum machines (heat engines, refrigerators, etc). Taking any interacting quantum system with arbitrary coupling to ideal reservoirs of electrons and bosons (phonons or photons), we identify symmetries between quantum trajectories and their time-reverses on the Keldysh contour. These lead to quantum fluctuations theorems the same as the well-known classical ones (Jarzynski and Crooks equalities, non-equilibrium partition identity, etc), but which hold whether the system's dynamics are Markovian or not. Hence, such systems obey the second law of thermodynamics on average, even if fluctuations may violate it. Our proof applies to systems with Kondo effects or other strong correlations, and to systems in superposition states or with time-dependent driving.

Implications of non-Markovian quantum dynamics for the Landauer bound‖

Marco Pezzutto[1], Mauro Paternostro[2], Yasser Omar[1]

[1]Universidade de Lisboa

[2]Queen's University Belfast - UK

Abstract: In many instances the widely employed Markovian description of the reduced dynamics of an open quantum system may fail in giving a good approximation of the real dynamics. The interaction with the environment can cause memory effects to be non-negligible, through what is commonly referred to as information backflow from the environment to the system. In many physical models of system-environment interaction memory effects turn out to affect heavily the dynamics of the system. In this work, we shed further light on the interplay between environmental memory effects and logical irreversibility in non-equilibrium processes. We construct

¶Preprint - arXiv:1611.00670

‖arXiv:1608.03497, soon to appear in New Journal of Physics.

a collisional model of the open-system dynamics of a spin-1/2 particle, the time evolution being realized through a sequence of discrete-time collisions, each ruled by a Heisenberg Hamiltonian, between the system and one environmental particle at a time. For non-interacting environmental particles all prepared in the same state, the system undergoes a homogenization dynamics: after a large number of collisions, the system's state is asymptotically driven towards the initial preparation of the environmental particles. Such homogenization is relatively robust against state fluctuations across the multiparticle environment. For an environment of interacting particles, instead, the effective dynamics that the system undergoes can be tuned broadly from a fully Markovian to a highly non-Markovian regime. The non-Markovianity of the dynamics is quantified with the Breuer-Laine-Piilo measure, based on the behaviour of the trace-distance of two different density states as they evolve in time under the combined system-environment dynamics. Collisions occurring between environmental subsystems have a twofold effect: on the one hand, they induce system-environment correlations resulting in memory effects that allow the environment to retain information on the state of the system at previous steps of its discrete-time evolution; on the other hand, they enable a feedback process whereby information is coherently brought back into the state of the system, thus steering its state in a distinguished way with respect to the corresponding homogenization dynamics. We unveil the implications that such a rich dynamics has for logical irreversibility, assessing the break down of Landauer principle as the non-Markovian character of the system's evolution is enhanced. In particular, we show a causal link between the system-environment correlations and the opening up of temporal windows in the time evolution of the system within which Landauer bound is no longer valid.

Large Deviation implies First and Second Laws of Thermodynamics

Hiroyasu Tajima, Eyuri Wakakuwa, Tomohiro Ogawa

Riken, Center for Emergent Matter Science - Japan

Abstract: To reconstruct thermodynamics based on the microscopic laws is one of the most important unfulfilled goals of statistical physics. Here, we show that the first law and the second law for adiabatic processes are derived from an assumption that "probability distributions of energy in Gibbs states satisfy large deviation", which is widely accepted as a property of thermodynamic equilibrium states. We define an adiabatic transformation as a probabilistic mixture of the energy-preserving unitary transformations on the many-body systems and the work storage. As the second law, we show that an adiabatic transformation from a set of Gibbs states to another set of Gibbs

states is possible if and only if the regularized von Neumann entropy becomes large. As the first law, we show that the energy loss of the thermodynamic systems during the adiabatic transformation is stored in the work storage as "work" in the following meaning:

(i) the energy of the work storage takes certain values macroscopically, in the initial state and the final state.

(ii) the entropy of the work storage in the final state is macroscopically equal to the entropy of the initial state.

As corollaries, our results give the maximum work principle and the first law for the isothermal processes. A mathematical proofs of this paper will be uploaded on the arXiv with the same title.

An operational formulation of thermodynamics makes the zeroth law obsolete

Philipp Kammerlander, Renato Renner

ETH Zurich - Switzerland

Abstract: In this talk I will focus on the specific findings which question the status of the thought-to-be fundamental 0th law in the standard derivation of thermodynamics as it is often encountered in textbooks and undergraduate courses. We introduce a new operational mathematical framework for classical phenomenological thermodynamics inspired by (quantum) information theory. By formulating a minimal set of operational assumptions we are able to rederive the theory's statements along standard lines not referring to ambiguous terms. While doing so, we prove a central theorem of phenomenological thermodynamics, Carnot's theorem on the efficiency of classical reversible cyclic thermal machines. We follow the standard proof of Carnot's theorem and, interestingly enough, do not have to refer to the 0th law of thermodynamics in the course of doing so. This is surprising given the fact that to our knowledge all standard proofs do. (The 0th law states that the relation among two systems "being in thermal equilibrium relative to each other" is an equivalence relation.)

The third law for finite non-equilibrium resources

Henrik Wilming, Rodrigo Gallego

FU Berlin - Germany

Abstract: Pure quantum states are indispensable resources for any task in quantum information processing. However, the third law of thermodynamics (more precisely, the unattainability principle) states that cooling a system

exactly to zero temperature requires an infinite amount of resources, being it in the form of time, space, work or some other resource. Here, we investigate in the amount of resources needed for approximate ground-state cooling. We consider as resource any system out of equilibrium, allowing for resources beyond the i.i.d. assumption and including the input of work as a particular case. We establish necessary and sufficient conditions for cooling in full generality and show that for a vast class of nonequilibrium resources sufficient and necessary conditions for low-temperature cooling can be expressed exactly in terms of a single function. This function plays a similar role for the third law as the free energy plays for the second law. From a technical point of view we provide new results about concavity/convexity of certain Renyi-divergences, which might be of independent interest.

Thursday 16^{th} March

Quantum chaos: A Jarzynski-like equality

Nicole Yunger Halpern

Caltech - United States

Abstract: The out-of-time-ordered correlator (OTOC) diagnoses quantum chaos and the scrambling of quantum information via the spread of entanglement. The OTOC encodes forward and reverse evolutions and has deep connections with the flow of time. So do fluctuation relations such as Jarzynski's Equality, derived in nonequilibrium statistical mechanics. I unite these two powerful, seemingly disparate tools by deriving a Jarzynski-like equality for the OTOC [1]. The equality's left-hand side equals the OTOC. The right-hand side involves a quasiprobabilitya quantum generalization of a probabilitywhere Jarzynskis Equality involves a probability. Just as Jarzynskis Equality facilitates the measurement of a free-energy difference F, this equality suggests a new scheme for measuring the OTOC. The scheme can be implemented with weak measurement or with interference. The equality opens holography, condensed matter, and quantum information to new insights from fluctuation relations and vice versa.

[1] N. Yunger Halpern, Phys. Rev. A 2017

Autonomous quantum machines and finite sized clocks **

Mischa Woods, Jonathan Oppenheim , Ralph Silva

University College London - UK

Abstract: Recent quantum thermodynamic resource theories and derivations of the second law in the quantum regime are predicated upon the unitary operation as a basic building block. The unitary itself is usually described by an external observer that manipulates an interaction. Including this control into a fully quantum description, a so-called “quantum clock”, is thus a critical step to placing quantum protocols on a firm footing, especially since due to information gain-disturbance principles, it is impossible to perform these operations perfectly. Here we present a quantum clock that performs a general

**arXiv:1607.04591

energy-preserving unitary autonomously with an error that is exponentially small in both the dimension and the energy of the clock.

The full quantum setup —system to be controlled plus clock— is described by a time independent Hamiltonian. This is crucial if one desires to understand the full quantum limitations to control, since a time dependent Hamiltonian would require external control, not explicitly accounted for. The main result is to show that this setup with a clock initially in a Gaussian superposition state can implement to any desired precision, any energy preserving unitary on the system during an arbitrarily small time interval with a back-reaction on the clock which is exponentially small in both energy and clock dimension. How fast as a function of energy and dimension the error in the back-reaction approaches zero is of paramount importance for understanding resource theories, since if the decay in error is too slow, one would have to invest a lot of work to correcting the error, representing an unaccounted for cost to quantum thermodynamic resource theories.

Previous to this work, it was only known that unitaries can be implemented perfectly in the infinite dimensional limit, from which it is impossible to estimate the thermodynamic cost of control. The model we present for the quantum clock is based on a model introduced by Eugene Wigner in General Relativity and later investigated in the non-relativistic regime by Asher Peres. Crucially, we consider a quantum superposition of so-called "clock states", in contrast to Asher's study. This is a crucial difference, which due to quantum constructive/destructive interference, leads to a much more accurate clock which can achieve the exponentially small error.

In conclusion, our work has implications for the validity of resource theories, and is both a benchmark for future implementations, as well as a conjecture on the fundamental limitations of clocks and control.

Finite-time dynamics and thermodynamics of open quantum systems

Vasco Cavina, Andrea Mari, Vittorio Giovannetti

Scuola Normale Superiore di Pisa - Italy

Abstract: We develop a perturbation theory of quantum (and classical) master equations with slowly varying parameters, applicable to systems which are externally controlled on a time scale much longer than their characteristic relaxation time. We apply this theoretical framework to the analysis of finite-time isothermal processes in which, differently from quasi-static transformations, the state of the system is not able to continuously relax to the equilibrium ensemble. Our approach allows to formally evaluate perturbations up to arbitrary order to the work, heat exchange and entropy production associated to an arbitrary process. Within first order in the perturbation ex-

pansion, we identify a general formula for the effciency at maximum power of a finite-time Carnot engine. We also clarify under which assumptions and in which limit one can recover previous phenomenological results as, for example, the Curzon-Ahlborn bound.

Quantum thermal machines driven by vacuum forces

Hugo Terças

Instituto de Plasmas e Fusão Nuclear, Lisbon - Portugal

Abstract: We propose a quantum thermal machine composed of two nanomechanical resonators (NMR) (two membranes suspended over a trench in a substrate). The quantum thermodynamical cycle is powered by the Casimir interaction between the resonators and the working fluid is the polariton resulting from the mixture of the fexural (out-of-plane) vibrations. With the help of piezoelectric cells, we select and sweep the polariton frequency cyclically. We calculate the performance of the proposed quantum thermal machines and show that high efficiencies are achieved thanks to (i) the strong coupling between the resonators and (ii) the large difference between the membrane stiffnesses. Our findings can be of particular importance for applications in nanomechanical technologies where a sensitive control of temperature is needed.

Recurrence of an isolated quantum many-body system

Bernhard Rauer

Vienna Center for Quantum Science and Technology - Austria

Abstract: Isolated quantum many-body systems undergoing unitary time evolution are expected to rephase back to their initial state after a certain amount of time. Yet for typical systems with many degrees of freedom this time is tremendously long prohibiting the observation of such recurrences. However- we show that by engineering a system described by an effective low energy theory of free commensurate phononic modes this recurrence can be shifted to experimentally accessible timescales even if thousands of particles are involved. - - Our model system is a pair of tunnel-coupled one-dimensional quasi-condensates which we take out of equilibrium by a fast ramp-down of the tunnel-coupling. In the subsequent evolution the relative phase field of the two condensates is monitored- providing a local probe for the system. This allows us to directly observe how the initial phase coherence between the two many-body systems is initially lost and later reemerges to a partial recurrence of the initial state.

Fluctuation theorem for pure quantum states

Takahiro Sagawa

University of Tokyo - Japan

Abstract: The origin of macroscopic irreversibility under microscopic reversible dynamics is a longstanding fundamental problem in nonequilibrium statistical mechanics. In recent years- it has been established that even a pure quantum state- described by a single wave function- can relax to macroscopic thermal equilibrium by reversible unitary dynamics. We here show that the second law of thermodynamics and the fluctuation theorem- a universal equality characterizing the property of entropy production far from equilibrium- hold true for isolated genuine quantum systems under unitary dynamics [1]. Our study is based on a rigorous proof by using the Lieb-Robinson bound- and numerical simulation of hard-core bosons. Our results imply that thermal fluctuations emerge from purely quantum fluctuations in nonequilibrium dynamics. We also discuss a role of Eigenstate-Thermalization Hypothesis (ETH).

[1] Eiki Iyoda, Kazuya Kaneko, Takahiro Sagawa, arXiv:1603.07857

Quantum supremacy of many-particle thermal machines

Adolfo Del Campo

University of Massachusetts - United States

Abstract: While the emergent field of quantum thermodynamics has the potential to impact energy science, the performance of thermal machines is often classical. We ask whether quantum effects can boost the performance of a thermal machine to reach quantum supremacy, i.e., surpassing both the efficiency and power achieved in classical thermodynamics. To this end, we introduce a nonadiabatic quantum heat engine operating an Otto cycle with a many-particle working medium, consisting of an interacting Bose gas confined in a time-dependent harmonic trap. It is shown that thanks to the interplay of nonadiabatic and many-particle quantum effects, this thermal machine can outperform an ensemble of single-particle heat engines with same resources, demonstrating quantum supremacy in many-particle thermal machines.

In the second part of the talk, we show that that nonadiabatic effects can be controlled and tailored to match the adiabatic performance using a variety of shortcuts to adiabaticity. As a result, the nonadiabatic dynamics of scaled-up many-particle quantum heat engine can exhibit no friction and the cycle can be run at maximum efficiency with a tunable output power.

J. Jaramillo, M. Beau, A. del Campo, *Quantum Supremacy of Many-Particle Thermal Machines*, New J. Phys. 18, 075019 (2016).

M. Beau, J. Jaramillo, A. del Campo, *Scaling-up quantum heat engines efficiently via short-cuts to adiabaticity*, Entropy 18, 168 (2016)

Optimal performance of generalized heat engines with finite-size baths of arbitrary multiple conserved quantities based on non-i.i.d. scaling

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[1]Nagoya University - Japan

[2]National University of Singapore - Singapore

Abstract: Recent explosion of studies on quantum thermodynamics have worked out fine-grained thermodynamic laws of small systems interacting with large baths. However, effects of finiteness of the baths has been less considered. We need to address that baths should be treated as finite resources where restricted size of the baths is accessible during the process. In particular, there is no prior research which focuses on finiteness of the baths of arbitrary multiple conserved quantities not only energy. Both practically and theoretically, finiteness of the (generalized) baths is much more significant in consideration of arbitrary multiple conserved quantities. Thus, we focus on how the optimal performance of generalized heat engines with multiple quantities alters in response to the scale. Though it is difficult to exactly calculate the performance in response to the scale, we resolve it by asymptotic approach, where we see the second leading order in scale reflecting finite-size effects. Furthermore, conventional researches on quantum thermodynamics have just considered scaling in terms of the number of identical copies of a system. Such scaling does not cover even such scaling as the volume of the container including the system. Then, we carry out all the analysis under an extension of the way of scaling to more natural way in consideration of asymptotic extensivity. Based on such generic way of scaling, we derive the bound of the optimal performance of generalized heat engines reflecting finite-size effects of the baths, which we call fine-grained generalized Carnot bound. Moreover, we construct a protocol to achieve the optimal performance, opening up non-i.i.d. based construction of protocols in quantum thermodynamics, which is also new for thermodynamic limit. Applying the general theory we establish, we deal with simple examples of generalized heat engines. One is a toy model of work extraction from a bath consists of two level particles by using two different direction of spin. This simple example illustrates interesting structures of finite-size regime, which is quite different from the thermodynamic limit, such as a resonance. The other is heat engine with baths consist of ideal gas exchanging particles whose size is given by the volume of the container. Although it is a canonical example of statistical mechanics, this is the first time to explicitly reveal the finite-size effects on the optimal performance of the engine.

Pure state quantum statistical mechanics

Christian Gogolin

ICFO - Spain, Max Planck Institute of Quantum Optics, Garching - Germany

Abstract: This tutorial constitutes a basic introduction into modern quantum - statistical mechanics and in particular recent developments concerning - equilibration and thermalization in closed quantum many-body systems. - We will see how equilibration and thermalization can be defined in - unitarily evolving and finite dimensional quantum systems- and under - what conditions they can be proved to happen. Also related discuss equilibration times- decoherence- and structural properties of thermal states of many-body systems.

[1] J. Eisert, M. Friesdorf, and C. Gogolin, *Nature Physics* 11, 124-130, (2015).

[2] C. Gogolin, and J. Eisert, *Reports on Progress in Physics* Volume 70, Number 5, 056001 (2016).

Sharing quantum coherence (and other asymmetries)

Joan Vaccaro

Griffith University, Brisbane - Australia

Abstract: Symmetry and their violations play fundamental roles in physics. Such is the case of coherence in quantum thermodynamics. Coherence, in its most general form, is the breaking of the symmetry represented by energy conservation. It is quantified by the entropic measure called asymmetry AG [1]. The talk will review the properties of asymmetry and report on a new result regarding the sharing of coherence. Coherence is found to be a finite resource that has limitations in the way it is shared among systems. An analysis in terms of asymmetry will then be used to resolve difficulties surrounding catalytic coherence [2].

[1] J.A. Vaccaro, F. Anselmi, H M. Wiseman and K. Jacobs, Phys. Rev. A 77, 032114 (2008).

[2] J. Aberg, Phys. Rev. Lett. 113, 150402 (2014).

Heat bath algorithmic cooling with correlated qubit-environment interactions

Nayeli A. Rodríguez-Briones[2], Jun Li[2], Xinhua Peng[1], Yossi Weinstein[3], Tal Mor[3], Raymond Laflamme[1,4,5]

[1] University of Waterloo - Canada
[2] University of Science and Technology of China, Hefei - China
[3] Technion-Israel Insitute of Technology, Haifa - Israel
[4] Perimeter Institute for Theoretical Physics, Waterloo - Canada
[5] Canadian Institute for Advanced Research, Toronto - Canada

Abstract: Pure states are needed for many quantum algorithms and in particular for quantum error correction. In many technologies, purification of qubits can be obtained through contact with a cold environment or by making specific measurements. In some other technologies however where only an ensemble is controlled, a different technique might be needed. Algorithmic cooling and its heat bath variant have been shown to purify qubits by clever redistribution of entropy and multiple contact with the bath, not only for ensemble implementations but also for technologies with strong but imperfect measurements. In this work, we remove an implicit restriction assumed in all previous work about the interaction with the bath and we show that more efficient cooling can be achieved. We introduce a novel tool for cooling algorithms which we have called state-reset. It can occur when the coupling to the

environment is not limited to qubit-resets, but could also include correlations between the qubits of the system. We present new cooling algorithms which lead to an increase of polarization beyond all the previous work, and relate our results to the Nuclear Overhauser Effect. Also, we show analytically the achievable polarization for the new method as a function of the number of qubits and as a function of the heat bath polarization.

Quantum Absorption Refrigerator in the Single-Shot Regime

Alexandre Roulet, Shiqian Ding, Gleb Maslennikov, Roland Hablutzel, Jaren Gan, Stefan Nimmrichter, Jibo Dai, Valerio Scarani, Dzmitry Matsukevich

National University of Singapore - Singapore

Abstract: We report on the experimental realization of a quantum absorption refrigerator, one of the standard examples of a heat machine, using the modes of trapped ytterbium ions. The refrigerator is evolving under the trilinear Hamiltonian $\hat{H} = \hat{a}^\dagger \hat{b} \hat{c} + \hat{a} \hat{b}^\dagger \hat{c}^\dagger$, where heat from the work mode b is transferred to the hot mode a, cooling down the cold mode c in the process. By implementing the refrigerator in the pulsed (or single-shot) regime, we experimentally cool down the cold mode c faster and to a lower occupation compared to the steady-state regime. We show theoretically that this feature is enabled by quantum coherence, as an incoherent evolution of the quantum refrigerator precludes the device from cooling further than the steady-state occupation. This is in agreement with previous predictions for qubit-based refrigerators and highlights the role of quantum coherence in improving the cooling efficiency of the quantum refrigerator. We also consider squeezed thermal states and find that they are not a useful resource for cooling further in the single-shot regime, comparing them with thermal states of the same average energy.

Quantum thermal machines based on microwave resonators coupled to a Josephson junction

Patrick P. Hofer[1], Jean Rene Souquet[2], Marti Perarnau-Llobet[3,4], Jonatan Brask[1], Ralph Silva[1], Marcus Huber[1,5], Aashish Clerk[2], Nicolas Brunner[1]

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[5]Institute for Quantum Optics and Quantum Information, Vienna - Austria

Abstract: We propose two thermal machines, a heat engine and an absorption refrigerator, based on microwave resonators coupled to a Josephson junction. Both machines are bosonic implementations of small thermal machines discussed in the literature. As such, they have universal efficiencies that only depend on the frequencies of the resonators and reach Carnot value at vanishing output power. For the heat engine, we find an intriguing separation of heat, which is carried by photons, and work, which is provided by Cooper pairs tunneling against a voltage bias. The proposed refrigerator is equipped with an on/off switch which allows for coherence enhanced cooling below the steady state temperature. Their smallness and conceptual simplicity make these machines ideal test-beds to study thermodynamics in quantum systems. Furthermore, we show that the machines are powerful and efficient for realistic system parameters.

Observation of the phononic Lamb shift with a synthetic vacuum

Fred Jendrzejewski

Kirchhoff-Institut für Physik, Heidelberg - Germany

Abstract: The Lamb shift in the spectrum of the hydrogenic atoms is one of the most precise experimental tools for the test of quantum electrodynamics. In this talk, we will present our observation of the phononic Lamb shift with a synthetic vacuum. We engineer the synthetic vacuum, building on the properties of ultracold atomic gas mixtures and observe the phononic Lamb shift using high-precision spectroscopy. Our observations establish this experimental platform as a new tool for precision benchmarking of experimental set-ups that mimic quantum electrodynamics with increasing sophistication.

A torque induced by matter waves as a new macroscopic quantum phenomenon

Alhun Aydin, Altug Sisman

Istanbul Technical University - Turkey

Abstract: When particles confined in nanodomains, they tend to stay away from the boundaries as a result of their wave nature. Local density distribution of a confined gas is non-uniform even in thermodynamic equilibrium since a quantum boundary layer (QBL) exists near to the domain walls. QBL modifies the thermodynamic properties of nanoscale systems which is a nice example of how size and shape of quantum confinement affects thermodynamics of such systems. An intriguing question then arises: Is it possible to propose new kind of macroscopic quantum effects based on shape-dependent modification of density distribution as a result of QBL? In this work, we present the existence of a torque induced by the wave nature of confined particles and emerging from the broken axial symmetry of confinement domain. To investigate such a torque, we propose a nanoscale confinement domain consist of two coaxial square wires. Outer wire (stator) is fixed, whereas inner wire (rotor) is free to rotate. The space between inner and outer wires is filled by a gas (atoms, electrons or photons etc.). Due to QBL, particles stay away

from boundaries and accumulate into the less confined regions of the domain. Therefore, spatial occupation of particles becomes non-uniform and pressure distributions along the walls of inner wire should also be non-uniform, which may lead to a torque. We make small angular perturbations by rotating the inner wire and solve Schrödinger equation numerically to obtain eigenvalues and eigenfunctions for each angular configuration. Then, we precisely calculate global free energy of confined gas by considering summations over discrete energy eigenvalues. We show that free energy changes periodically with angular position of inner wire. Consequently, a torque emerges on the inner wire due to the variation of free energy with angle. Local density distribution is also calculated using eigenvalues and eigenfunctions, to get some physical insight for the explanation of this quantum torque. Errors due to meshing and truncation procedures are also analyzed and we show that the magnitude of the proposed effect is much bigger than the numerical errors. It's a quantum phenomenon, since the torque effect vanishes when Planck's constant goes to zero. Meanwhile, it's a macroscopic quantum effect because the torque persists even if the size of the wires in the direction of rotational axis is larger than nanoscale. Novel quantum thermodynamic devices may be designed based on this torque.

Work Extraction and All Electrical Detection of the Landauer Principle in a Quantum Spin Hall Device

Inanc Adagideli

Sabanci University, Istanbul - Turkey

Abstract: Landuer's principle states that erasure of each bit of information in a system requires at least a unit of energy $k_B T \ln 2$ to be dissipated. In return, the blank bit may possibly be utilized to create $k_B T \ln 2$ per bit of usable work, in keeping with the second law of thermodynamics. While in principle any collection of spins can be utilized as information storage, energy/work extraction by utilizing this resource in principle requires specialized engines/machines that are capable of using this resource. In this work, we focus on heat and charge transport in a quantum spin Hall device, in the presence of a spin bath. We show how a properly initialized spin bath can be used as a (Maxwell's demon memory) resource to induce charge current in the device that can power an applied external electrical load, using avaliable heat energy from electrical reservoirs that couple to the device via electrical contacts. We also show how to intialize the spin bath using applied bias currents, that neccesarily dissipate energy, hence demonstrating Landauer's principle, as well as an alternative method of "energy storage" in an all electrical device. We finally propose a realistic setup to experimentally observe a Landauer erasure/work extraction cycle.

Poster session

Tuesday 14^{th} March, 18:30

Performance of superadiabatic quantum machines

Obinna Abah, Eric Lutz

FAU Erlangen-Nuremberg - Germany

Abstract: We investigate the performance of a quantum thermal machine operating in finite time based on shortcut-to-adiabaticity techniques. We compute efficiency and power for a quantum harmonic Otto engine by taking the energetic cost of the superadiabatic driving explicitly into account. We further derive generic upper bounds on both quantities, valid for any heat engine cycle, using the notion of quantum speed limits for driven systems. We demonstrate that these quantum bounds are tighter than those stemming from the second law of thermodynamics.

A Minimal Set of Experimental Operations in Quantum Thermodynamics

Edgar Aguilar Lozano, Micha Horodecki, Hanna Wojewodka

University of Gdańsk - Poland

Abstract: Thermal Operations seem to describe the most fundamental, and reasonable, set of operations allowable for state transformations at a background temperature T. However they require experimentalists to manipulate very complex environments, and have control over their internal degrees of freedom. For this reason, the community has been working on creating more experimentally-friendly operations, with the hope of one day testing the limits of quantum thermodynamics in a lab. In this work we ask whether in the context of Coarse Operations, ancillas are necessary to simulate all thermal operation transformations. This is with the aim of establishing a minimal set of experimental operations, which would be of great help for experimental implementations.

Petz recovery map, dynamical semigroups, and quantum thermodynamics

Alvaro Alhambra[1], Mischa Woods[1], Stephanie Wehner[2], Mark Wilde[3]

[1]University College London - UK
[2]Delft University - The Netherlands

[3]Louisiana State University - USA

Abstract: Existing research programs try to look at what insights we can gain about the thermodynamics of small systems inspired by ideas from quantum information theory. We present a definite example of this connection through a tool called the Petz recovery map, which is used to measure how well one can recover quantum information after a general quantum map.

A series of recent results aim to give a lower bound to the decrease of quantum information, understood as the decrease of relative entropy, in terms of how well one can recover, via a so-called "recovery map", an initial state after applying a general quantum map. We argue that the idea of analysing how well quantum information can be recovered intersects very well with the spirit of thermodynamics, where we want to gauge the irreversibility of dissipative processes.

We will discuss two papers which use these ideas and concepts from quantum information theory to quantum thermodynamics:

1. In the context of dynamical semigroups, and Davies maps in particular, we prove a strong case of these lower bounds, which is known to not be true in general. We show how it can be used to obtain a relation between the entropy production after time t and how much the state changes after time 2t. This relation constitutes a tight bound that imposes strong constraints on how systems reach thermal equilibrium. The key point is that for dynamical semigroups with the property of quantum detailed balance, the Petz recovery map of the dissipative evolution coincides with the map itself. Hence, the recovery map does not actually recover but dissipates even more. Surprisingly, the resultant bound is both universal and tight.

2. We also show, in the context of resource theory approaches to quantum thermodynamics, how the bound on entropy production can be used to link the irreversibility of a transition between states to how much work could have been extracted along the same transition. We show that this is true for various classes of operations, namely Gibbs preserving operations, thermal operations, catalytic thermal operations and catalytic thermal operations in which the catalyst becomes correlated with itself after the energy preserving unitary. What is interesting is that in every case, the resulting recovery map also belong to the same class of operations.

Quantum thermal devices indirectly connected to environments

Daniel Alonso, Jose Pascual Palao, and Javier Onam Gonzalez

Universidad de La Laguna - Spain

Abstract: A quantum thermodynamics network is composed of thermal devices connected to different environments through quantum systems modelling quantum wiries. The steady state currents are sistematically decomposed into different contributions corresponding to simple circuits present in the abstract graph representing the master equation equation of the system. Each single circuit represents a simple mechanism in the machine operation and its performance can be understood in terms of a reduced set of circuits.

Autonomous Rotor Heat Engine

Alexandre Roulet, Stefan Nimmrichter, Juan Miguel Arrazola, Valerio Scarani

Centre for Quantum Technologies - Singapore

Abstract: The triumph of heat engines is their ability to convert the disordered energy of thermal sources into useful mechanical motion. In recent years, much effort has been devoted to generalizing thermodynamic notions to the quantum regime, partly motivated by the promise of surpassing classical heat engines. Here, we instead adopt a bottom-up approach: we propose a realistic autonomous heat engine that can serve as a testbed for quantum effects in the context of thermodynamics. Our model draws inspiration from actual piston engines and is built from closed-system Hamiltonians and weak bath coupling terms. We analytically derive the performance of the engine in the classical regime via a set of nonlinear Langevin equations. In the quantum case, we perform numerical simulations of the master equation and find that free dispersion and measurement backaction noise generally lower the engine's performance.

Quantum heat engine with a mixed triangular spin system

Ekrem Aydiner, Deniz Han

Istanbul University - Turkey

Abstract: Quantum heat engines (QHEs) are devices that convert heat into work described by the laws of quantum statistical mechanics. They have been a subject of intense research due to their great practical applications. Unlike a classical heat engine, in QHEs, the energy exchange between the system and thermal reservoirs occurs in quantized fashion. Therefore the QHEs are modeled as sets having discrete energy levels unlike classical engines. In recent times, various efforts have been made to understand the working mechanism of QHEs. The current active fields in quantum thermodynamics include QHEs work-extraction processes from quantum systems, conditions of positive work and so on. QHEs produce work using quantum systems, such as the spin system, harmonic oscillator system two-level or multilevel system,

cavity quantum electrodynamics system and coupled two-level system as the working substances.

In this study, we consider mixed Heisenberg XXZ mixed $(1/2, 1, 1/2)$ spin system on a simple triangular cell. So far, many spin models have been investigated, however, to best our knowledge heat engine behavior in mixed spin system with all possible magnetic ordering has never been studied. The triangle mixed spin system, which can be mapped into one dimensional lattice, can produce rich phase behavior such as ferrimagnetic, ferromagnetic, antiferromagnetic and spin glass depending on interaction couplings between spins. In many theoretical studies researchers focus the understanding of the QHE behavior in the most known magnetic phases such as ferromagnetic, antiferromagnetic systems since they have many theoretical and technological importance. Here we must remark that the ferrimagnetic systems have also great importance in technological applications and on the other hand, the more less known spin glasses which are known frustrated systems have also many important properties and there are many relation between spin glass system and many other physical systems in areas as diverse as computer science, neural networks, prebiotic evolution, protein conformational dynamics, protein folding and a variety of others. Therefore, investigation of quantum thermodynamic behavior in ferrimagnetic and spin glass systems are also important as well in other magnetic systems.

With these motivations, in this study, we investigate the triangle Heisenberg XXZ mixed $(1/2, 1, 1/2)$ spin system. We show that this system behaves as a four-stroke quantum Otto engine with positive work for all possible magnetic phase ordering. We also present results of work and efficiency of this engine as well as in other magnetic ordering.

Electromagnetic gauge-freedom and work

Sanasar Babajanyan, Armen Allahverdyan

A. I. Alikhanian National Science Laboratory (Yerevan Physics Institute) - Armenia

Abstract: We argue that the definition of the thermodynamic work done on a charged particle by a time-dependent electromagnetic field (EMF) is an open problem, because the particle's Hamiltonian is not gauge-invariant. The solution of this problem demands accounting for the source of the field. Hence we focus on the work done by a heavy body (source) on a lighter particle when the interaction between them is electromagnetic and relativistic. The work can be defined via the gauge-invariant kinetic energy of the source. We uncover a formulation of the first law (or the generalized work-energy theorem) which is derived from relativistic dynamics, has definite validity conditions, and relates the work to the particle's Hamiltonian in the Lorenz gauge. Thereby the thermodynamic work also relates to the mechanic work done by the Lorentz

force acting on the source. The formulation of the first law is based on a specific separation of the overall energy into those of the source, particle and EMF. This separation is deduced from a consistent energymomentum tensor. Hence it holds relativistic covariance and causality.

Typical relaxation dynamics to equilibrium, thermal or non-thermal, of isolated many-body quantum systems

Ben Niklas Balz, Peter Reimann

Bielefeld University - Germany

Abstract: In the recent past, typicality arguments were used extensively to corroborate that isolated quantum many-body systems equilibrate and that the associated steady state is naturally given by the microcanonical ensemble. These statements are usually derived making use of uniformly distributed unitary transformations (Haar measure) and therefore do not take conserved quantities into account. In the following we are going to present an adapted typicality technique, employ it to derive the corresponding relaxation dynamics and present numerical as well as experimental data in its support.

Stochastic thermodynamics of boundary driven quantum systems

Felipe Barra

Universidad de Chile [Santiago] - Chile

Abstract: In some processes, quantum systems are isolated or driven by a time dependent parameter for a while, coupled to a probe or environment for another lapse of time, measured at some instant of time and so on. During the coupling to the environment heat may ow to the system but also work may be performed on the system. This work may be neglected in a weak coupling regime but otherwise it is important to account for it in the thermodynamic description. We develop the stochastic thermodynamics appropriate for these processes [1], analyze the fluctuation properties of this work and show that in a suitable limit the system dynamics can be described by a Lindblad equation with dissipators that not only manifest the heat exchange with the environment but also the work due to the coupling [2]. We illustrate our results for processes involving spin XX and XY chains.

[1] F. Barra and C. Lledó in preparation

[2] F. Barra, Sci. Rep. 514873 (2015).

The thermodynamic cost of quantum operations

Daniel Bedingham, Owen Maroney

University of Oxford - UK

Abstract: The amount of heat generated by computers is rapidly becoming one of the main problems for developing new generations of information technology. The thermodynamics of computation sets the ultimate physical bounds on heat generation. A lower bound is set by the Landauer Limit, at which computation becomes thermodynamically reversible. For classical computation there is no physical principle which prevents this limit being reached, and approaches to it are already being experimentally tested. In this paper we show that for quantum computation with a set of signal states satisfying given conditions, there is an unavoidable excess heat generation that renders it inherently thermodynamically irreversible. The Landauer Limit cannot, in general, be reached by quantum computers. We show the existence of a lower bound to the heat generated by quantum computing that exceeds that given by the Landauer Limit, give the special conditions where this excess cost may be avoided, and provide a protocol for achieving the limiting heat cost when these conditions are met. We also show how classical computing falls within the special conditions.

Using thermodynamics to identify quantum subsystems

Almut Beige[1], Adam Stokes[2], Prasenjit Deb[3]

[1]University of Leeds - UK
[2]University of Manchester - UK
[3]Bose Institute - India

Abstract: There are many ways to decompose the Hilbert space of a composite quantum system into tensor product subspaces. Different subsystem decompositions generally imply different interaction Hamiltonians V, and therefore different expectation values for subsystem observables. This means that the uniqueness of physical predictions is not guaranteed, despite the uniqueness of the total Hamiltonian H and the total Hilbert space. Here we use Clausius' version of the second law of thermodynamics (CSL) and standard identifications of thermodynamic quantities to identify possible subsystem decompositions [1]. It is shown that agreement with the CSL is obtained, whenever the total Hamiltonian and the subsystem-dependent interaction Hamiltonian commute (i.e. $[H, V] = 0$). Not imposing this constraint can result in the transfer of heat from a cooler to a hotter subsystem, in conflict with thermodynamics. We also investigate the status of the CSL with respect to non- standard definitions of thermodynamic quantities and quantum subsystems.

[1] A. Stokes, P. Deb and A. Beige, arXiv:1602.04037 (2016)

An operational derivation of Jaynes' Principle

Paul Boës, Rodrigo Gallego, Henrik Wilming, and Jens Eisert

FU Berlin - Germany

Abstract: Jaynes principle states that a system should be assigned that state which has the largest entropy of those that are compatible with the available knowledge. Jaynes himself argued for the principle based on information theoretic least bias considerations. Here, we prove an operational version of Jaynes' Principle: We show that there exists an equivalence relation between resource theories whose states are "macroscopic", based on partial information about a system's state, and resource theories whose states are just the corresponding maximum entropy states, in the sense that state transitions in one theory are possible if they are possible in the other. This equivalence arguably provides a better-suited operational justification for the application of Jaynes' Principles in a discipline like quantum thermodynamics than Jaynes' own argument. For quantum thermodynamics, the relevance of the results is that it shows the equivalence between a resource theory of thermal operations under partial information and that of equilibrium thermodynamics, thus providing a simple and elegant insight into the connection between thermal equilibrium dynamics and limited operational control over systems.

In this talk, I will present the proof and discuss its relevance. The basic object in a setting of partial information, say the expectation value a with respect to some observable A, is a macrostate, which is the set $[a]$ of all quantum states whose expectation value with respect to A is a. The key step of the proof is a protocol that lets us map any state in $[a]$ into the maximum entropy states with certainty, with the help of free macrostates drawn from some fixed class $[a']$ and a source of randomness. Importantly, we do so without changing the overall expectation value of the system and ancillary systems. Also, for instance for the case of A being the Hamiltonian, the fluctuations in the work in this protocol, can be shown to obey a central limit theorem, meaning that any deviation from the Jaynes' Principle vanishes as the system becomes increasingly large.

This work fits within a range of recent efforts to clarify and generalise resource theories in the context of quantum thermodynamics, for instance the study of the unique form of free states in Helmholtz theories, or resource theories for several, possibly non-commuting observables. Another area of active research that it contributes to is that of devising resource theories with realistic operational control on the experimenter's part.

Quantum Thermodynamics for Cosmology

Chester Moore[1], André Xuereb[2], Chaitanya Joshi[3], David Bruschi[3]

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[2]University of Malta - Malta
[3]University of York - UK

Abstract: Understanding the fundamental laws of our Universe is one of the most important quests in physics. Quantum field theory in curved spacetime, our best attempt to merge quantum mechanics and relativity, has provided the background arena to understand cosmological phenomena and evolution. Classical thermodynamics, employed in this context, has led to groundbreaking discoveries and predictions, such as radiating black holes. Cosmological processes can be fundamentally quantum in nature and classical thermodynamics fails at providing the ultimate correct picture of the role of energy, entropy and work in relativistic and quantum contexts.

In this work we employ quantum thermodynamics to explore simple relativistic and quantum scenarios. Our goal is to understand energy and entropy ows and the exchanges between matter and gravitational degrees of freedom, an aspect that is poorly understood. We will build on a preliminary result that suggests that statistical uctuations around mean values provide a different understanding of the role of matter in the entropy production in the universe. We propose a toy model that mimicks dynamical gravitational scenarios. We show that it is possible to consider energy-conserving time evolution of the whole system while tracking the sources and employers of energy and entropy, whether gravitational or quantum in nature. We then pin point the role of the gravitational degrees of freedom and discuss the main features of our model.

This novel approach opens the possibility of understanding the role of gravity in quantum processes, such as the expanding universe, from a completely new perspective.

Geometrical properties of dissipative driven phase transitions

Angelo Carollo[1,2], Bernardo Spagnolo[1,2], Davide Valenti[1]

[1]University of Palermo - Italy

[2]Lobachevsky State University, Nizhny Novgorod - Russia

Abstract: We discuss geometrical properties associated to reservoir-induced phase transitions of lattice fermions in non-equilibrium steady-state of an open system with local reservoirs. These systems may become critical in the sense of a diverging correlation length on changing the reservoir coupling. In analogy with Halmitonian quantum phase transitions, such criticality is associated with a vanishing gap in the damping spectrum, and correspondingly, with a point of non-analicity in the parameter space of the steady-state solutions. We show that such a point of non-analicity can induce a curvature in steady-state manifold, that can be observed through the Uhlmann geometric phase. Indeed, we show that the curvature associated by Uhlmann geometric phase shows a finite discontinuity at the point of criticality. This behaviour is reminiscent, and, in fact connected, to the divergence of the fidelity susceptibility.

Optimal power output for a single level quantum dot heat engine

Vasco Cavina[1,2], Alberto Carlini[3], Andrea Mari[1,2], Vittorio Giovannetti[1,2]
[1] Scuola Normale Superiore di Pisa - Italy
[2] NEST Istituto Nanoscienze-CNR, Pisa - Italy
[3]Università degli Studi del Piemonte Orientale-Amedeo Avogadro - Italy

Abstract: We study the thermodynamics of an heat engine based on a single level quantum dot and paired with two thermal baths of different temperature. Our aim is to maximize the power output of the engine for a cycle in a finite amount of time, through the control of some external parameters. In order to do this we describe the dynamics of the system using a quantum master equation that depends on three possible controls: the energy level of the quantum dot and two couplings that regulate the exchange of heat with the two thermal baths.

We consider the maximum power achievable in a fixed time, thus reducing the problem to a minimization of the total work done during the process. Our results provide a generalization of the achievements of Esposito et Al. for the single bath scenario and are obtained using some advanced technics of optimal control theory. The optimal protocols turn out to be composed by a sequence of two fundamental sub-transformations, that have respectively the peculiarity of being instantaneous or that of requiring the decoupling from one of the two heat baths. The transformation of the first kind don't involve any exchange of heat and are thus adiabatic, while those of the second kind can be considered isothermal.

We conclude with a detailed analysis of the properties of those sub-processes: it is interesting to notice that not only the isothermal sub-processes are different from the reversible ones (as it is legitimate to expect in a scenario in which only a finite amount of time is available) but also the adiabatic sub-processes are described by different relations from those that regulates a reversible Carnot or Otto cycle. Then, although the general structure of the optimal processes is similar to that of a reversible Carnot engine, with cold and hot isothermal transformations separated by single adiabatic transformations, the detailed structure of each of the fundamental sub-transformations is very different and represents a peculiarity of the system. Some of the results we obtained for the single level quantum dot can be generalized to a wider class of heat engines.

Thermodynamic description of non-Markovian information flux in non-equilibrium open quantum systems

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[2]QCMRG, CEMS, RIKEN, Saitama - Japan,

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[4] National Center for Theoretical Sciences - Taiwan, [5]University of Michigan - United States

Abstract: One of the fundamental issues in the open quantum systems is the nature of non- Markovianity, which has attracted divergent interest in many fields. There are also different measures of non- Markovianity proposed recently. Here, by invoking the interplay between thermodynamics and information theory, we explicitly specify the information flux in an open quantum system using the thermodynamic quantity and present a simple protocol to show that a system attempts to share this information with its environments and establish the system-environment correlations. We also show that the retrieved information from an environment characterizes the non-Markovianity and indivisibility of the system dynamics. Finally, we show that the externally induced coherence in photocells and biologically inspired quantum heat engines not only enhances the performance, but also gives rise to indivisibility, implicit non-Markovianity, and the information flux inversion.

Superadiabatic quantum heat engine with a multiferroic working medium

Levan Chotorlishvili

Martin Luther University Halle-Wittenberg - Germany

Abstract: A quantum thermodynamic cycle with a chiral multiferroic working substance such as LiCu2O2 is presented. Shortcuts to adiabaticity are employed to achieve an efficient, finite- time quantum thermodynamic cycle, which is found to depend on the spin ordering. The emergent electric polarization associated with the chiral spin order, i.e., the magnetoelectric coupling, renders possible steering of the spin order by an external electric field and hence renders possible an electric-field control of the cycle. Due to the intrinsic coupling between the spin and the electric polarization, the cycle performs an electromagnetic work. We determine this work's mean-square fluctuations, the irreversible work, and the output power of the cycle. We observe that the work mean-square fluctuations are increased with the duration of the adiabatic strokes, while the irreversible work and the output power of the cycle show a nonmonotonic behavior. In particular, the irreversible work vanishes at the end of the quantum adiabatic strokes. This fact confirms that the cycle is reversible. Our theoretical findings evidence the existence of a system inherent maximal output power. By implementing a Lindblad master equation we quantify the role of thermal relaxations on the cycle efficiency. We also discuss the role of entanglement encoded in the noncollinear spin order as a resource to affect the quantum thermodynamic cycle.

Applications of the Stochastic Liouville-von Neumann (SLN)

Equation to Quantum Technology

Claudia Clarke, Ian Ford

University College London - UK

Abstract: As nanoscale manipulations become increasingly feasible, a better understanding of quantum thermodynamics is required to improve our understanding of microscopic structures and subsequently increase the efficiency of operations on this scale. Various techniques currently exist to model the thermodynamic properties of quantum systems, but these generally rely on approximations. An exact method is the stochastic Liouville-von Neumann equation [1], based on unravelling Feynman-Vernon influence functionals [2]. We here extend its use from the one heat bath case [3] to consider the thermodynamic behaviour, including heat flow, of a system in a non-equilibrium stationary state brought about by coupling to more than one heat bath. We develop this yet further to begin to consider using the SLN to model quantum systems, which could be used to experimentally realise quantum technologies such as heat engines and/or refrigerators. One scheme potentially amenable to modelling with the SLN equation is the recently proposed absorption refrigerator which used coupling to heat baths [4]. Quantum thermodynamics experiments (such as electronic refrigeration [5]) have been performed, so there is scope to compare SLN models with experimental data.

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Merits and Qualms of Work Fluctuations in Classical Fluctuation Theorems

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[2]University of Augsburg - Germany

Abstract: Work is one of the most basic notion in statistical mechanics, with work fluctuation theorems being one central topic in nanoscale thermodynamics. With Hamiltonian chaos commonly thought to provide a foundation for classical statistical mechanics, here we present general salient results regarding how (classical) Hamiltonian chaos generically impacts on nonequilibrium work fluctuations. For isolated chaotic systems prepared with a micro-

canonical distribution, work fluctuations are minimized and vanish altogether in adiabatic work protocols. For isolated chaotic systems prepared at an initial canonical distribution at inverse temperature β, work fluctuations depicted by the variance of $e^{-\beta W}$ are also minimized by adiabatic work protocols. This general result indicates that if the variance of $e^{-\beta W}$ diverges for an adiabatic work protocol, then it diverges for all nonadiabatic work protocols sharing the same initial and final Hamiltonians. How such divergence explicitly impacts on the efficiency of using the Jarzynski's equality to simulate free energy differences is studied in a Sinai model. Our general insights shall boost studies in nanoscale thermodynamics and are valuable in designing useful work protocols.

System bath correlations and the nonlinear response

Arend Dijkstra

University of Leeds - UK

Abstract: Complex systems are often described in a system bath picture. When both the system and the bath are modeled quantum mechanically, quantum correlations between the system and the bath can be present. They can influence the dynamical properties of the system. In a microscopic theory, there are three major effects of the bath on the system. The first two are dissipation, which removes excess energy from the system, and fluctuations, which supply energy. These two effects are related through the fluctuation-dissipation theorem, which assures that the correct finite temperature equilibrium state is reached. The third one are the correlations between system and environment states, which are well known in the fields of nonlinear optics and NMR and are a key property in open system dynamics and quantum information. These correlations are almost always present if the bath is described quantum mechanically. They are the characteristic quantity, which causes the system state to become mixed when interacting with a bath. This third effect plays a major role if the system bath interaction is strong, or if the characteristic time scale of the noise induced by the environment is slow or similar compared to typical system time scales. It is the origin of a rephasing signal in photon echo and NMR echo measurements. This means that system bath correlations can be probed in such nonlinear measurements. The memory effects that underlie these experiments can result not only from the dynamics, but also from the initial conditions. Examples of system variables that are influenced by system bath correlations are system entanglement, non-Markovianity as well as energy and heat transport. We study system bath correlations and their signature in experiment using numerical techniques, in particular, the hierarchy of equations of motion, and exactly solvable models.

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Testing fluctuation theorems for quantum open systems in an engineered environment

Cyril Elouard[1], Nadja Bernardes[2], Andre Carvalho[3], Marcelo Santos[4], Alexia Auffevesz[1]

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[2]Universidade Federal de Minas Gerais - Brazil,
[3]Department of Quantum Science (ANU) - Australia,
[4]Instituto de Fisica, Rio de Janeiro - Brazil

Abstract: Research on stochastic thermodynamics has allowed to derive the famous Fluctuation Theorems, i.e. equalities linking out-of-equilibrium thermodynamic quantities to equilibrium properties of a system undergoing a thermodynamic transformation. While several experimental tests of these theorems have been implemented, the case of quantum open systems remains out of reach. Here we propose a realistic setup to test experimentally quantum Jarzynski equality for a driven two-level atom in contact with a heat bath. An engineered environment allows to detect photons emitted and absorbed by the atom and compute the heat ow. We evidence that quantum effects can be observed in that setup, e.g. that the quantization of the the entropy production and its crucial consequence which is that missing a single photon may endanger the verification of the Fluctuation Theorem. We show in particular that if the detectors used in the engineered environment have an imperfect detection efficiency, a deviation from Jarzynski equality is expected. We predict a correction term, that can be computed from the imperfect measurement record, which has to be integrated in the Jarzynski equality to recover 1. This study provides a significant step towards experimental verification of Fluctuation Theorems in quantum open systems.

Fundamental limits for cooling of linear quantum refrigerators

Jose Nahuel Freitas, Juan Pablo Paz

Instituto de Física de Buenos Aires (IFIBA) - Argentina

Abstract: We study the asymptotic dynamics of arbitrary linear quantum open systems which are periodically driven while coupled with generic bosonic reservoirs. We obtain exact results for the heat owing from each reservoir, which are valid beyond the weak coupling or Markovian approximations. We prove the validity of the dynamical third law of thermodynamics (Nernst unattainability principle), showing that the ultimate limit for cooling is imposed by a fundamental heating mechanism which dominates at low temperatures: the non resonant creation of excitation pairs in the reservoirs

induced by the driving field. This quantum effect, which is missed in the weak coupling approximation, restores the unattainability principle whose validity was recently challenged.

Thermodynamics with local control

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Abstract: We investigate the limitations that emerge in thermodynamic tasks as a result of having only local control over the components of the thermal machine. These limitations are specially relevant for machines composed of strongly interacting many-body systems. More particularly, here we investigate protocols of work extraction that employ as a working medium a many-body system whose evolution can be driven by tuning only the on-site Hamiltonian terms. This provides a restricted set of thermodynamic operations and new bounds for the performance of engines. Our findings show that those limitations in control make it in general impossible to reach Carnot efficiency and sometimes even forbid to reach a finite efficiency or work per particle. We focus on the 1d Ising model in the thermodynamic limit as a case study, for which we show that in the limit of strong interactions the ferromagnetic case becomes useless for work extraction, while the anti-ferromagnetic improves its performance with the strength of the couplings, reaching Carnot in the limit of arbitrary strong interactions. Our results provide a promising connection between Quantum Control and thermodynamics and introduce more realistic set of operations well suited to current experimental scenarios.

Energy quantization, heat machines and machine learning

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Abstract: In this work, we go back to the basic property of energy quantization in trapped single-particle systems that operate as heat machines. We focus on the Otto cycle which describes the ideal operation of the internal combustion engines and is easier to implement than the Carnot cycle. One of the fundamental paradigms of the classical version of the Otto cycle involves the compression ratio, $r = V_c/V_h$, where V_c and V_h are the volumes of the combustion chamber at equilibrium with the cold and hot bath, respectively. No work is extracted for $r < 1$ and a large r is required for high efficiency. Nevertheless, in realistic applications, such as airplanes and automobile engines, the possibility of spontaneous ignition sets a practical upper bound on

the compression ratio, limiting their efficiency well below the fundamental Carnot limit.

Here we show that even though quantum engines are limited by Carnot's bound, for certain confining potentials, energy quantization can improve the actual performance of heat machines relatively to their classical counterpart and may even change their operation mode: quantum mechanics may "fix" a classical broken heat machine (which neither extracts work, nor refrigerates) or even "transform" a classically expected engine to a quantum refrigerator, or vice versa. We compare the thermodynamic output, i.e, extracted work or heat, with and without energy quantization and show that the former can be more efficient, invalidating the well-known efficiency equation for an Otto engine and in principle lifting any fundamental restriction to the creation of highly efficient engines with compression ratios even below one.

Finally, in order to understand which features of the trapping potentials favor the heat machine performance and the quantum supremacy we use Bayesian Optimization, a novel machine learning approach for gradient-less optimization of black-box functions. By considering parametrized potentials and solving their quantum mechanical properties, we can efficiently search for promising setups of quantum machines that could be further validated experimentally.

Towards QFI maximising entangled matter-wave interferometry in BECs

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Abstract: The endeavour to optimally apply matter-wave interferometry has generated many proposals and prototypes of ultra-sensitive rotational, gravitational/inertial and gravity wave detection protocols. Optimal protocols should fully exploit the characteristics of BECs and should aim to be Heisenberg limited through entanglement or number-squeezing and have globally equivalent classical and quantum Fisher information (QFI). Optical trapping allows us to exploit internal atomic spin degrees of freedom, in particular by allowing simultaneous trapping of atoms in different magnetic sublevels. A useful method of controlling such spinor condensates is topological vortex imprinting, where the texture of externally applied time-varying magnetic fields (B-fields), usually employed to create magnetic traps, is embedded in the condensate.

We propose a method of matter-wave interferometry which splits a repulsively interacting spinor condensate into a superposition of both spin and super ow states. This spin-orbit coupled interferometry (SOCI) procedure

uses topological vortex imprinting as a beam-splitter in the momentum and spin bases, achieved through the use of the B-field. The "arms" of the interferometer are not necessarily spatially split, allowing for the creation of a common-path interferometer, which is insensitive to a variety of perturbing factors due to its intrinsic symmetry. A noteworthy application of the common-path method is zero-area Sagnac interferometry (ZASI), often discussed as an alternative to the Michelson geometry for optical gravity-wave detection.

Characterization of the quantumness of a spin based quantum engine

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Abstract: We report the experimental characterization of the non-classical nature of an engine performing an Otto like cycle in a finite time, employing a spin-1/2 system as a working substance. To characterize the quantumness of this engine we use the Legget-Garg inequality, analogously to what is proposed in Ref. [1]. We have implemented such an engine in a liquid-state nuclear magnetic resonance (NMR) setup [2,3], and we have tested the Leggett- Garg macrorealism condition by means of an interferometric quantum circuit [4].

The thermodynamic cycle implemented consists of four strokes; composed by two processes without heat exchange, where an external time modulated magnetic field is applied to perform (extract) work on (from) the nuclear spin and two thermalization processes. In the thermalization step we implemented a partial thermalization through a quantum channel and an ancillary quantum system, all together this mimic a finite time action of a thermal reservoir. In our experiment we present a full characterization of a quantum thermal machine with partial termalization, including different regimes of operation. Furthermore, we show through the measurement of the Leggett-Garg function, how the degree of thermalization affects the coherence in the quantum thermodynamic cycle.

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Experimental observation of a quantum thermodynamic signature, and the quantum engine type equivalence effect

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Abstract: A quantum thermodynamic signature is a thermodynamic measurement that indicates the presence of a quantum agent (e.g., interference, entanglement). By measuring the work output of heat engines in room temperature in NV centers in diamonds, we show that the power output exceeds a bound derived on stochastic machines. The measurement validates the presence and dominance of a quantum coherence-based work extraction mechanism. In addition, in the same setup we experimentally observe the low action equivalence effect between continuous machines and two-stroke machine that was predicted recently. To the best of our knowledge these findings are the first to show intrinsically quantum thermodynamic features in heat machines.

Combining baths by adding dynamical generators

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Abstract: In order to describe dynamics of a quantum system that thermalizes being in contact with a bath, while potentially also interacting with other systems, one derives the effective master equations that determines the system evolution. In particular, one identifies the dynamical generator, which can be interpreted as a superoperator acting solely on the system, that contains all the information about the particular type of interactions. In order to model the interactions with multiple baths and systems, it is often assumed that their corresponding dynamical generators can be simply added. In our work, we systematically identify under what conditions such an approach is correct. We first prove that by adding already simple generators, e.g., representing Markovian evolutions, non-physical dynamics may be even obtained. Hence, when combining reservoirs one should always return to the microscopic derivation, for which we provide an explicit condition stating when adding baths is tantamount to adding their corresponding generators. We explicitly show that such condition is also generally not fulfilled even when all the interaction Hamiltonians commute with one another, and with the system one. Yet, we provide a useful sufficient condition that can be always verified basing on the Hamiltonian structure without explicitly solving the dynamics. Lastly,

we focus on the open-system approximations in order to explicitly prove that in the weak coupling regime, in which the time-convolution-less approach is valid up to the second order (encompassing, e.g., the Born-Markov regime), one can always combine baths by simply adding their dynamical generators.

Heat Machines driven by strong coupling and non-Markovian dynamics and non-Markovian spectroscopic signature.

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Abstract: In a system-bath scenario how can we know from the the systems observables that the dynamics is non Markovian. I will present an experimental spectroscopic signature based on the difference in weak field absorption between a positive and negative chirped pulse which is is such a signature. We model the non-Markovian bath using the Stochastic Surrogate Hamiltonian where the bath is a set of spins. Thermal boundary conditions are imposed by random swaps with an auxiliary spin bath at temperature T. I will describe the performance characteristics of a heat rectifier and a heat pump in a non-Markovian framework using the Stochastic Surrogate Hamiltonian. The device is constructed from a molecule connected to a hot and cold reservoir. The dynamics are driven by a combined systembath Hamiltonian. The temperature of the baths is regulated by a secondary spin bath composed of identical spins in thermal equilibrium. The combined system is studied in various systembath coupling strengths. In all cases, the average heat current always ows from the hot towards the cold bath in accordance with the second law of thermodynamics. The asymmetry of the double well generates a rectifying effect, meaning that when the left and right baths are exchanged the heat current follows the hot-to-cold direction. The heat current is larger when the high frequency is coupled to the hot bath. Adding an external driving field can reverse the transport direction. Such a refrigeration effect is mod- elled by a periodic driving field in resonance with the frequency difference of the two potential wells. A minimal driving amplitude is required to overcome the heat leak effect. In the strong driving regime the cooling power is non-monotonic with the systembath coupling.

Possibility theory in quantum thermodynamics

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Abstract: In this report the possibility theory is applied to open quantum systems. In this theory instead of ‘probability amplitudes’ one uses ‘degrees

of belief'. It is supposed that this approach can not be treated as 'new interpretation' of the quantum probability theory because it is very important in cases where statistical methods are not applicable. For example, the possibility theory makes sense when one deals with macroscopic unique (improbable) quantum states of open quantum systems and corresponding unrepeatable (improbable) transformations. Therefore, the possibility theory is not in conflict with the quantum probability theory and, maybe, it is the only way to deal with macroscopic open quantum systems.

Quantum Flywheel

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Abstract: In this work we present the concept of a quantum flywheel coupled to a quantum heat engine. The flywheel stores useful work in its energy levels, while additional power is extracted continuously from the device. Generally, the energy exchange between a quantum engine and a quantized work repository is accompanied by heat, which degrades the charging efficiency. Specifically when the quantum harmonic oscillator acts as a work repository, quantum and thermal fluctuations dominate the dynamics. Quantum monitoring and feedback control are applied to the flywheel in order to reach steady state and regulate its operation. To maximize the charging efficiency one needs a balance between the information gained by measuring the system and the information fed back to the system. The dynamics of the flywheel are described by a stochastic master equation that accounts for the engine, the external driving, the measurement, and the feedback operations.

Optimal coherence preservation in the presence of a dissipative environment

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Abstract: Quantum coherence is a crucial resource for quantum information tasks, from computation to metrology, but it is easily destroyed by interaction with a dissipative environment. The classical dynamics of populations and the decoherence process are, however, intimately related, as illustrated by the famous relation between T1 and T2 times in the optical Bloch equations. In this work we develop a general bound, valid for any finite-dimensional system, providing the minimum amount of decoherence compatible with a given stochastic dynamics of population. The result only relies on two as-

sumptions, Markovianity and the secular approximation, and as such it is applicable to a vast range of models. Moreover, we prove the bound to be tight for a variety of initial conditions. A simple application highlights the role of non-Markovianity for the preservation of quantum coherence in a thermalisation process. Our relation provides a general tool for estimating the resilience of quantum information in a dissipative environment that requires only knowledge of the classical dynamics of populations.

Quantum simulation of single-qubit thermometry using linear optics

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Abstract: Thermodynamics aims at the investigation of open systems looking at the exchange of energy in the form of either work or heat. Even though it developed in order to study systems in equilibrium with the surrounding environment, lately thermodynamics has been the object of extensions for treating irreversibility, non-equilibrium quantum processes, and transient behaviours. The simplest example of an open system considers a single particle in direct contact with an external reservoir resulting in original thermometry applications. Conventional thermometry begins with thermal equilibrium states and aims to explore ensuing changes in macroscopic states after the thermalisation with the external reservoir. A different thermometry approach aims to reduce the dimensions of the probe and in pushing away from the thermalisation timescale to finally obtain a temperature measurement response: such requirements lies in the emergence of small thermometers for nanoscale experiments and in the possibility of measuring non-equilibrium thermal bath temperatures. These concepts can be analyzed using quantum simulated dynamics, reflecting in the possibility to isolate effects stemming genuinely from the process of interest, decoupling all spurious behaviours from other unwanted interactions, and guaranteeing experimental reproducibility. Here we want to discuss the simulation in a linear-optical setup of a single-qubit thermometry capable of discriminating between two reservoirs at different, but known, temperatures. Being thermodynamics a theory depicting state transformation in the presence of an external reservoir, we introduce a phenomenological model for this interaction as a Generalized Amplitude Damping Channel to simulate the thermometry protocol discussed by Jevtic and coworkers. Our simulator encodes the probe qubit in the polarisation, and the coupling to the external bath via the spatial mode of light. We take the approach of considering how well the single-qubit thermometer can effect its task in out-of-equilibrium conditions: limiting the interaction time,

thus avoiding thermalisation, results in an improved temperature discrimination. Our results show that the coherence between the energy levels of the qubit helps making the temperature discrimination more robust, allowing for an enhanced discrimination over the thermalised case for longer times compared with the case of simple energy eigenstates: we identify the origin of this behaviour in their different thermalisation dynamics by the change in the Helmholtz free energy.

Thermodynamics of a bipartite quantum system

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Abstract: The generalization of the laws of thermodynamics for strongly interacting quantum systems is an open issue. Concerning the first law, the definitions of heat and work are still debated because one has to evaluate the contribution of the interaction Hamiltonian. Moreover, the internal entropy production rate of a system is always non-negative if its dynamics is described by a time-dependent Lindblad generator, but usually this is not the case when the environment is finite and strongly interacting. We tackle this issue considering a generic bipartite quantum system, initially prepared in a product state, and studying the energy and entropy exchange in time between the interacting subsystems [1]. By properly defining heat, work and entropy production at the microscopic level, we can write a generalized version of the first and second law of thermodynamics that highlights the role of correlations and interaction. Some interesting features of this formulation can be illustrated by a simple example, namely a qubit undergoing dephasing due to the coupling with a bath of harmonic oscillators. This model is important because it is analytically solvable and many physical quantities are computed exactly, without the usual weak-coupling approximation.

S. Alipour, F. Benatti, M. Afsary, F. Bakhshinezhad, S. Marcantoni, and A. T. Rezakhani, Sci. Rep. 6, 35568, (2016)

Free energy for non-equilibrium quasi-stationary states

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Abstract: We study a class of non-equilibrium quasi-stationary states for a Markov system interacting with two different thermal baths, where the work done under a slow, external change of parameters admits a potential, i.e. the free energy. Three conditions are needed for the existence of free energy in this non-equilibrium system: time-scale separation between variables of the system, partial controllability (external fields couple only with the slow

variable), and an effective detailed balance. These conditions are facilitated in the continuous limit for the slow variable. In contrast to its equilibrium counterpart, the non-equilibrium free energy can increase with temperature, i.e cooling from a higher temperature may be easier (in the sense of the work cost) than from a lower.

The Extended Stochastic Liouville-von Neumann Equation for an Open Quantum System

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Abstract: We consider an open quantum system interacting with a harmonic bath, using a generalisation of the Caldeira-Leggett (CL) Hamiltonian in which the bath's oscillators are internally coupled and the interaction term is arbitrary in the system coordinates. The influence functional formalism is utilised to generate a path integral expression for the reduced density matrix pertaining to the open system of interest. This is done assuming that initially the whole system is fully equilibrated with the environment (the partition-free approach as opposed to the partitioned one of Feynman and Vernon). The resultant path integral describing the reduced density matrix is then transformed via a two-time Hubbard-Stratonovich transformation, introducing a stochastic field for each environmental oscillator. This leads to a set of differential equations for the reduced density matrix, termed the Extended Stochastic Liouville-von Neumann (ESLN) equation. This is an exact solution that is valid even when considering transient effects far from equilibrium. This approach generalises and synthesises previous work based on partitioned CL models, as well as non-partitioned equilibrium path integral descriptions of open systems.

Leggett-Garg inequalities for uctuating work

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Abstract: A set of Leggett-Garg inequalities for the statistics of fluctuating work done on a system driven out of equilibrium are derived. It is shown that quantum systems can violate these inequalities, demonstrating that fluctuations in work in the quantum regime exhibit non- classical features that cannot be replicated through any classical non-equilibrium process. This clarifies that the fluctuating work cannot generally be interpreted as a classical stochastic variable due to violations of so-called macrorealism at the quantum level. Importantly, this behaviour is distinct from both measurement disturbance and quantum coherence, as the violations of the inequalities can

be observed both non-invasively and independent of temperature. Instead these non-classical work statistics arise from temporal correlations between the energy states occupied by the system at different times along the process. Our work helps to elucidate the influence of temporal correlations on work extraction within quantum non-equilibrium thermodynamics.

Autonomous quantum clocks: how thermodynamics limits our ability to measure time

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Abstract: Time remains one of the least well understood concepts in physics, most notably in quantum mechanics. A central goal is to find the fundamental limits of measuring time. One of the main obstacles is the fact that time is not an observable and thus has to be measured indirectly. Here we explore these questions by introducing a model of time measurements that is complete and self-contained. Specifically, our autonomous quantum clock consists of a system out of equilibrium —a prerequisite for any system to function as a clock— powered by minimal resources, namely two thermal baths at different temperatures. We find that the laws of thermodynamics imply a fundamental trade-off between the amount of dissipated heat and the clock's performance in terms of its accuracy and resolution. We present both universal arguments and an explicit model to illustrate this behaviour. Our results show that entropy production according to the second law of thermodynamics is a resource for timekeeping. More generally, autonomous clocks provide a natural framework for the exploration of fundamental questions about time in quantum theory and beyond.

Deterministic work extraction from passive states via projective measurements

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Abstract: In order to cyclically extract work from a system that is in a passive state, an irreversible process must be utilised. The paradigmatic example of such a process is a standard projective measurement. If, in addition, we wish to extract the same quantity of work for all measurement outcomes, the observable we measure must be mutually unbiased with respect to the

Hamiltonian. We show that in order to achieve this, one must either perform work during the measurement process, or the measurement apparatus must be infinitely large.

Measuring the arrow of time in a hybrid opto-mechanical system

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Abstract: Irreversibility is a fundamental concept of thermodynamics, associated with the existence of time arrow for thermodynamic transformations. The degree of irreversibility of a transformation is quanti

ed by entropy production, which can be defined at the level of single realizations. The fluctuations of such entropy production verify the celebrated fluctuation theorems, e.g. Jarzynski's equality [1, 2]. To measure entropy production, the usual strategy is to monitor the trajectory of the small system under study. If it gave rise to successful experimental demonstrations in the classical regime [3, 4], this strategy can become problematic in the quantum regime, because of measurement back- action. To probe fluctuation theorems, we propose another strategy based on the direct measurement of work fluctuations. More precisely, we shall exploit a hybrid optomechanical system, i.e. a two-level system (TLS) coupled to a mechanical oscillator on the one hand, and to optical photons on the other hand. It was shown in [5] that the mechanical oscillator plays the role of a battery, exchanging work with the TLS. Work exchanges can be measured, by measuring the mechanical energy at the beginning and at the end of the transformation. Here we go beyond these first results and show that mechanical fluctuations can be related to work fluctuations, providing a direct way to measure fluctuation theorems. We finally evidence that Jarzynski's and Crooks equalities [1, 2] can be probed in state of the art devices.

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Performance of a quantum heat engine at strong reservoir coupling

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Abstract: Traditional treatments of heat engines are within the approxi-

mation of weak coupling between the working system and the heat reservoirs. Recently, it has been shown that the Reaction Coordinate formalism offers one possible approach for analyzing heat engines which operate at strong coupling [1,2]. We employ this formalism in the study of a discrete stroke, finite time Otto cycle and demonstrate how finite coupling between the system and heat reservoirs is beneficial over the weak coupling limit when seeking to optimize the power output of the engine.

[1] arXiv:1609.04035.

[2] New J. Phys. 18 073007

Surpassing Carnot effciency by extracting imperfect work

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Abstract: A suitable way of quantifying work for microscopic quantum systems has been constantly debated in the field of quantum thermodynamics. One natural approach is to measure the average increase in energy of an ancillary system, called the battery, after a work extraction protocol. This is the most commonly used measure, since it greatly simplifies the analysis. The quality of energy extracted is usually argued to be good by quantifying higher moments of the energy distribution, or by restricting the amount of entropy generated. However, this only partially limits the amount of heat contribution to the energy extracted, instead of completely preventing it. We show that the definition of work is crucial, especially when analyzing the performance of particular heat engine protocols. We propose a characterization of work into several different regimes, according to the ratio of entropy increase within the battery with respect to the amount of energy extracted. If one allows for a definition of work that tolerates a non-negligible entropy increase in the battery, then even a small-scale heat engine can possibly exceed the Carnot efficiency. This can be done without exhausting any additional resources such as quantum coherence or correlations, and furthermore can already be achieved even when one of the heat baths is finite in size, for example being a single qubit. The surpassing of Carnot efficiency, which seems to contradict our classical understanding of heat engine performances, is due to the fact that the work extracted is imperfect, or in other words, the energy extracted is non-negligibly tainted by heat contributions. Therefore, our results highlight the importance of using a correct work quantifier while analyzing heat engine performances. We also investigated the fundamental maximum efficiencies for all quantum heat engines, given different types of work quality according to our characterization. Since the maximum achievable efficiency is different for

different types of work quality, our results may also serve as a guideline in claiming optimality for a particular heat engine protocol, while taking into account the quality of work extraction achieved.

Thermodynamics of continuously measured quantum systems

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In thermodynamics, access to a heat bath of infinite size is a very standard assumption. In particular, the bath is usually taken to have a divergent heat capacity. When we have access to such a bath, the difference in free energy between the initial and final states quantifies how much work we can extract when evolving the state of a system under a thermodynamical process. This is a good approximation when the time of the interaction is long enough, and a large number of degrees of freedom can be reached, but in other regimes we expect finite-size corrections to become relevant. In this work we calculate such corrections, by examining how thermodynamical processes are limited when we drop this infinite size idealization. We see that quantities such as the work extractable from a state, or the work required to create it from a thermal state, can no longer be written as differences of free energies. Moreover, we show how these quantities are fundamentally bounded by a correction to the free energy that depends on the heat capacity of the bath, both in the fluctuating and deterministic work scenarios. In particular cases such as Landauer erasure or state formation we derive a tight upper bound in terms of the varentropy, a second-order information measure

Thermodynamics of continuously measured quantum systems

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Abstract: In a continuous measurement process, a driven quantum system exchanges energy with a coupled detector. Here we analyze the thermodynamic properties of a driven quantum system continuously coupled to a quantum detector in the weak measurement regime and introduce definitions of work and heat along individual quantum trajectories that are valid for coherent superpositions of energy eigenstates.[1] We use these quantities to extend the first and second laws of stochastic thermodynamics to the quantum domain. We illustrate our result for a driven two-level system and show how to distinguish between work and heat contributions. We employ a continuous feedback protocol to suppress the detector backaction and determine the work statistics. We finally discuss the implementation of the proposed pro-

tocols for experiments with superconducting (transmon) qubits in resonant cavities, where single quantum trajectory tracking has been demonstrated. [1]

J. J. Alonso, E. Lutz, and A. Romito, Phys. Rev. Lett. 116, 80403 (2016).

Entropy rise is a closed system

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Abstract: One of the most used uncertainty measures in quantum systems is the von Neumann entropy. Despite its huge success it has some serious limitations. For example it stays constant in a closed system. This is the same as assuming we have the ability to track the evolution of every single particle which might not be always possible. Moreover such an entropy cannot describe a simple scenario in which a small number of particles expand into a larger space which we could intuitively view as rising entropy. We define a new uncertainty measure that is one of the quantum mechanical equivalents of the Boltzmann entropy, and describe some of its properties. We argue that such a measure is exactly the right measure for describing scenarios where the von Neumann entropy fails. Finally we discuss its possible application in information engines.

Quantum Thermodynamics with Bohmian Mechanics

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Abstract: One of the persisting problems in the formulation of quantum thermodynamics is the unambiguous definition of work for processes starting from an energy superposition [1]. There are currently a few proposals in the literature [2-4] but they do not always agree, especially when dealing with higher moments. At the root of the problem is the fact that quantum mechanics offers no clear concept of energy when the system is in an energy superposition. From a pragmatic point of view, there is no unambiguous way of writing down an energy balance equation for an arbitrary process.

Bohmian mechanics offers an alternative formulation of non-relativistic quantum mechanics. The appealing aspect of bohmian mechanics is that energy, position, work, etc, can be defined unambiguously for any state of the system. In particular, an energy balance equation follows straight from the Schrödinger equation. For these reasons, the framework of stochastic thermodynamics can be readily applied. Motivated by recent weak measurement results and its connection to bohmian mechanics, we show how to define work and entropy for arbitrary processes using the combined frameworks of

bohmian mechanics and stochastic thermodynamics. Furthermore, a integral fluctuation theorem will be shown to follow naturally from this framework.

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Purity in microcanonical thermodynamics: a tale of three resource theories

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Abstract: Thermodynamics is one of the most successful paradigms of physics, with applications ranging from engineering to chemistry, biology, and computation. In recent years, developments in the field of nanotechnology have raised novel questions about thermodynamics away from the thermodynamic limit. Resource theories provide a valuable framework for studying thermodynamics in this new regime. Specifically, for systems with definite energy, the key resource is purity. This results calls for a deeper understanding. Indeed, is this a mere consequence of the Hilbert space formalism of quantum mechanics, or is there an information-theoretic underpinning thereof? To answer this question, we formulate three resource theories of purity in the framework of general probabilistic theories (GPTs). Each resource theory corresponds to a different choice of free operations, including i) random reversible operations, ii) noisy operations, generated by reversible interactions with ancillas in the microcanonical state, and iii) unital operations, which preserve the microcanonical state. We determine the requirements the underlying GPT should satisfy in order to support well-behaved resource theories with the above sets as free operations. Then, we focus on a special class of physical theories, called sharp theories with purification, which are appealing for an information-theoretic foundation of thermodynamics. For every sharp theory with purification we show that the convertibility of states implies the validity of a majorisation condition. Moreover, we characterise exactly when majorisation is sufficient for convertibility via random reversible operations: precisely, the sufficiency of majorisation is equivalent to the requirement that every maximal set of perfectly distinguishable pure states can be reversibly converted into any other such set. Under this condition, we prove that i) random reversible, noisy, and unital operations obey inclusion relations like in quantum theory, ii) despite being different, the three sets of operations are equivalent in terms of convertibility, iii) there exists a one-to-one correspon-

dence between measures of purity and Schur-convex functions, and iv) purity resources are dual to entanglement resources.

On the role of non-Markovianity in the thermodynamics of driven open quantum systems

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Abstract: Thermodynamic machines are open systems (at least part-time) arising the question if memory effects do play a role in their dynamics, whether detrimental or as a possible resource. Here, we examine non-Markovian effects in different open quantum systems, where information back ow can result either from cold reservoirs or structured environments. We discuss heat ow, work and cooling in these settings. Also, we investigate the influence of optimised driving.

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The power of an optical Maxwell's demon in the presence of photon-number correlations

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Abstract: Recently, Vidrighin et al. [1] demonstrated an optical realization of Maxwell's Demon. A two-mode optical field impinges on two photodiodes and the electric charges thence emitted are used to charge a capacitor. The two modes carry independent fields with identical thermal distribution. Therefore, in the absence of the demon, the capacitor will acquire no charge on average.

The Demon is incorporated into this setup by inserting a high transmittance beam splitter before the photodiode. The reflected light from the beam splitter is coupled to a single photon detector, allowing the Demon to gain some information about the beam. With the measurement results, feedforward is applied allowing the Demon to charge up the capacitor.

Our work expands on this by exploring how photon number correlations will affect the efficacy of the Demon. We consider the following three correlations: 1) The classical number correlated state (split thermal state), achieved by sending a thermal state through a beam splitter, 2) The quantum number correlated state (two mode squeezed state) and 3) The number anti-correlated state (mixture of NOON states). We note that the power of the Demon is hindered in the correlated state and enhanced in the number anti-correlated state, which is analogous to the effect of correlation on a thermal Maxwell's

Demon. This spurred us on to further consider the resource theory of thermodynamics in particular, the concept of passivitivity. A state is passive if its energy cannot be decreases by applying any energy-preserving unitary operations. From the results of our study, we find that Maxwell's Demon is incommensurable with state preparation with regards to passitivity.

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Escape from a driven Quantum Metastable State: Stabilization by Dissipation and Resonant Activation

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Abstract: We investigate first how the combined effects of strong Ohmic dissipation and monochromatic driving affect the stability of a quantum system with a metastable state. We find that, by increasing the coupling with the environment, the escape time makes a transition from a regime in which it is substantially controlled by the driving, displaying resonant peaks and dips, to a regime of frequency-independent escape time with a peak followed by a steep fall off. The quantum noise enhanced stability phenomenon is observed in the system investigated. Secondly, we analyze the resonantly activated escape from a quantum metastable state by tunneling in the spin-boson model at strong Ohmic dissipation in the presence of fluctuating and periodical driving fields. Resonant activation, the presence of a minimum in the mean escape time, occurs when the time scale of the modulations is the same as the characteristic time scale of the system's dynamics, essentially determined by dissipation-induced renormalization of the bare tunneling amplitude. The simple quantum system considered displays as well the general features that at slow modulations the mean escape time is dominated by the slowest configuration assumed by he system, while at fast modulations the escape dynamics is determined by the average configuration.

Thermal machines can extract work from any passive state

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Abstract: Carnot engines are devices able to extract work while performing a cyclic process between a hot and a cold thermal reservoir. How-

ever, one can consider a less idealised situation in which the reservoirs are not completely thermalised at a specific temperature, and can be described by passive states (i.e those states from which no work can be extracted with a unitary transformation). We consider this latter scenario, and we present an engine which extracts work while individually interacting with the passive states of a single reservoir. The protocol utilises an ancillary system (the "thermal machine") whose local state is preserved during the cycle, so that we can use it during multiple cycles. We show that work can be extracted from any passive state using this engine, except for completely passive states (Gibbs states at any positive temperature, and the ground state). Indeed, the closer a passive state is to the set of completely passive states, the bigger the dimension of the ancillary system has to be. Our result provides a way to unlock part of the energy contained in a single passive state, while only using a finite-dimensional ancilla. It also suggests a more physically meaningful distinction between the notion of passive and completely passive states.

Autonomous Quantum Heat Engine Using an Electron Shuttle

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Abstract: Recent theoretical work [1, 2] has shown how certain thermodynamic laws should be modified in quantum systems with a few degrees of freedom. However, these new laws of quantum thermodynamics are highly abstract and do not admit a clear, unambiguous physical interpretation consistent with our many intuitive notions from classical thermodynamics. This motivates the development of a simple quantum device that can be used as a playground in order to test and elucidate some of these abstract notions.

Towards this end, we propose a simple quantum heat engine based on a single-electron shuttle. This system was studied in [3] in the zero temperature limit, where it behaved as a mesoscopic electric motor driven by an external electric bias. In contrast, our heat engine is a single-electron shuttle between two Fermi seas with identical chemical potentials but a temperature difference. Electrons can move from the high-temperature bath (source) to the low-temperature region (drain) via the shuttle. The shuttle feels a force, when it carries an electron, due to the Jonson noise. Since the average of the Johnson noise is zero, we need a rectifier to direct the force toward the drain. The rectifier can be achieved by letting the shuttle oscillate in a half-harmonic potential.

With this model, we can define and calculate work and heat, thereby allowing us to test abstract notions from quantum ther- modynamics. Specifically, work is defined as the dissipation of phonons into a zero temperature bosonic bath, whilst heat ow can be calculated via the current through the shuttle.

As a final addition, we show how output work from this engine can be stored in a quantum ratchet battery.

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Efficiency bounds on quantum thermoelectric heat engine with magnetic fields: the role of inelastic processes

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Abstract: Quantum thermoelectric heat engine is a steady-state (or autonomous) heat engine that converts heat to electric power. It has been argued that breaking time-reversal symmetry is a way to achieve a high thermoelectric efficiency. Benenti et al. recently claimed [1] that in this case one can achieve the Carnot efficiency with a finite power, which appears to contradict the second law of thermodynamics. In order to investigate this claim and to obtain a high efficiency, we consider a quantum thermoelectric heat engine made of an Aharonov-Bohm ring threaded by a magnetic flux, incorporating electron-phonon inelastic scattering [2]. The model has a quantum dot and three reservoirs; two electronic reservoirs and a bosonic one. Electrons are inelastically scattered by phonons at the quantum dot.

Putting an electronic heat current to be zero, we reduce the original model with three reservoirs to the effective model with two reservoirs (an electronic one and a bosonic one) and calculate the effciency of generating power by a phononic heat current.

With this model, we find the following two results [3]: First, we find that, contrary to Benenti's claim [1], such a device cannot reach the Carnot efficiency with a finite magnetic field because of the non-negativity of the entropy production of the original model with three reservoirs; Second, we find that breaking time-reversal symmetry can enhance the thermoelectric efficiency by phonons significantly beyond the one without phonons. For example, the efficiency at maximum power can reach 90% of the Carnot efficiency for some parameters.

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Towards a quantum heat engine with single ion

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Abstract: Thermodynamics plays very an important role in nature and it is one of the most robust theories in physics. However when it comes to quantum limit, meaning quantum fluctuations playing an important role in the system, very little has been investigated theoretically and more so experimentally. Among different quantum systems, ion traps are particularly useful in investigating thermodynamics close to the quantum limit due to their near isolation and controlled interaction. A single ion in an ion trap is a harmonic oscillator which can be prepared in a particular motional state with high fidelity. The trap potential allows possible steps of a heat engine or refrigerator to be implemented along with addressing lasers which effectively acts as heat bath. In this presentation we would like to share the proposed heat engine with a single ion and also some preliminary results on certain steps of the engine. In the process we would also discuss the challenges in implementing a fully cycle as well as the measurement strategies.

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